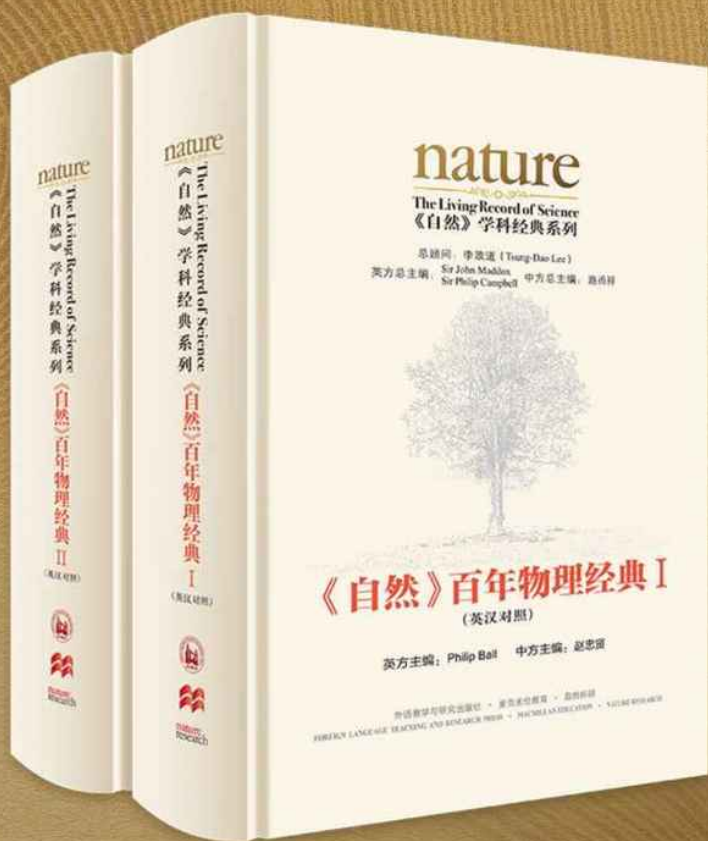


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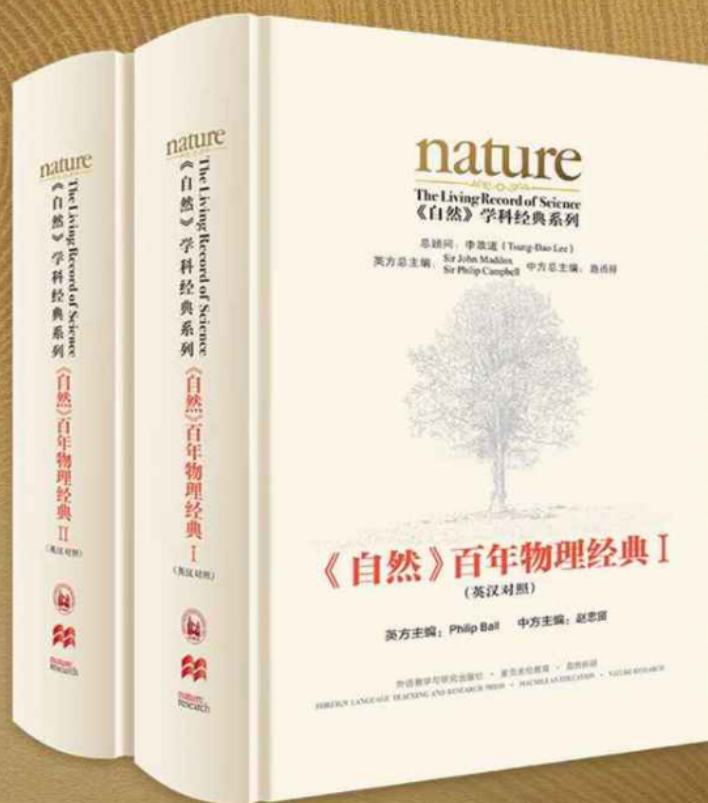
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总目录

[《自然》百年物理经典I](#)

[《自然》百年物理经典II](#)

nature

The Living Record of Science
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总顾问：李政道 (Tsung-Dao Lee)

英方总主编：Sir John Maddox 中方总主编：路甬祥
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FOREIGN LANGUAGE TEACHING AND RESEARCH PRESS · MACMILLAN EDUCATION · NATURE RESEARCH
北京 BEIJING

Original English Text © Springer Nature Limited

Chinese Translation © Foreign Language Teaching and Research Press

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图书在版编目 (CIP) 数据

《自然》百年物理经典 . I : 英汉对照 / (英) 菲利普·鲍尔 (Philip Ball) , 赵忠贤主编 . ——北京 : 外语教学与研究出版社 , 2020.9

(《自然》学科经典系列)

ISBN 978-7-5213-1945-3

I . ①自... II . ①菲... ②赵... III . ①物理学 - 文集 - 英、汉 IV .
①O4-53

中国版本图书馆CIP数据核字 (2020) 第126022号

地图审图号 : GS (2020) 3943号

出 版 人 徐建忠

项目统筹 章思英

项目负责 刘晓楠 王丽霞

责任编辑 王丽霞

责任校对 黄小斌

封面设计 孙莉明 高蕾

版式设计 孙莉明

出版发行 外语教学与研究出版社

社 址 北京市西三环北路19号 (100089)

网 址 <http://www.fltrp.com>

印 刷 北京华联印刷有限公司

开 本 787×1092 1/16

印 张 57

版 次 2020年8月第1版 2020年8月第1次印刷

书 号 ISBN 978-7-5213-1945-3

定 价 568.00元

购书咨询：(010) 88819926 电子邮箱：club@fltrp.com

外研书店：<https://waiyants.tmall.com>

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目录

Foreword by Tsung Dao Lee

李政道序

Foreword by Lu Yongxiang

路甬祥序

Foreword by Philip Ball

菲利普·鲍尔序

1869

The Atomic Controversy

原子论战

1870

Mathematical and Physical Science

数学和物理科学

1871

On Colour Vision

论色觉

The Copley Medalist of 1870

1870年的科普利奖章获得者

1873

Clerk Maxwell's Kinetic Theory of Gases

克拉克·麦克斯韦的气体动力学理论

Molecules

分子

1875

On the Dynamical Evidence of the Molecular Constitution of
Bodies

关于物体分子构成的动力学证据

1880

Maxwell's Plan for Measuring the Ether

麦克斯韦测量以太的计划

Clerk Maxwell's Scientific Work

克拉克·麦克斯韦的科学工作

1896

On a New Kind of Rays

论一种新型的射线

Professor Röntgen's Discovery

伦琴教授的发现

New Experiments on the Kathode Rays

关于阴极射线的新实验

1897

The Effect of Magnetisation on the Nature of Light Emitted by a Substance

磁化对物质发射的光的性质的影响

1913

Intra-atomic Charge

原子内的电荷

The Structure of the Atom

原子结构

The Reflection of X-rays

X射线的反射

1919

Einstein's Relativity Theory of Gravitation

爱因斯坦关于万有引力的相对论

1921

A Brief Outline of the Development of the Theory of Relativity

相对论发展概述

Atomic Structure

原子结构

The Dimensions of Atoms and Molecules

原子和分子的尺度

1923

Waves and Quanta

波与量子

1927

Thermal Agitation of Electricity in Conductors

导体中电的热扰动

The Scattering of Electrons by a Single Crystal of Nickel

镍单晶对电子的散射

The Continuous Spectrum of β -rays

β 射线的连续谱

1928

A New Type of Secondary Radiation

一种新型的二次辐射

Wave Mechanics and Radioactive Disintegration

波动力学和放射性衰变

1930

The “Wave Band” Theory of Wireless Transmission

无线传输的“波带”理论

Electrons and Protons

电子和质子

Artificial Disintegration by α -particles

α 粒子引发的人工衰变

Fine Structure of α -rays

α 射线的精细结构

The Proton

质子

The Ether and Relativity

以太与相对论

Unit of Atomic Weight

原子量的单位

1931

Evidence for a Stellar Origin of the Cosmic Ultra-penetrating Radiation

宇宙超穿透性辐射起源于恒星的证据

Present Status of Theory and Experiment as to Atomic Disintegration and Atomic Synthesis

原子衰变与原子合成的理论和实验现状

New Aspects of Radioactivity

放射性研究的新面貌

The End of the World: from the Standpoint of Mathematical Physics

以数学物理的视角看宇宙的终点

Obituary

讣告

The Annihilation of Matter

物质的湮灭

Quantum-mechanical Models of a Nucleus

原子核的量子力学模型

The Angular Momentum of Light

光的角动量

Isolated Quantised Magnetic Poles

孤立的量子化磁极

Maxwell and Modern Theoretical Physics

麦克斯韦与现代理论物理

1932

Experimental Proof of the Spin of the Photon

光子自旋的实验证据

The Decline of Determinism

决定论的衰落

News and Views

新闻与观点

Artificial Production of Fast Protons

快质子的人工产生

Possible Existence of a Neutron

可能存在中子

Determinism

决定论

Determinism

决定论

Disintegration of Lithium by Swift Protons

由快质子引起的锂衰变

The Cry of Tin

锡叫

The Neutron Hypothesis

中子假说

New Evidence for the Neutron

关于中子的新证据

Mechanism of Superconductivity

超导电性机理

1933

Disintegration of Light Elements by Fast Protons

快质子引起的轻元素衰变

Energy of Cosmic Rays

宇宙射线的能量

Helium Liquefaction Plant at the Clarendon Laboratory, Oxford

牛津大学克拉伦登实验室的氦液化车间

Recent Researches on the Transmutation of the Elements

关于元素嬗变的最新研究

Light and Life

光与生命

Nuclear Energy Levels

核能级

New Evidence for the Positive Electron

有关正电子的新证据

Nature of Cosmic Rays

宇宙射线的性质

A Possible Property of the Positive Electron

正电子可能具有的性质

Positrons and Atomic Nuclei

正电子和原子核

Magnetic Moment of the Proton

质子的磁矩

Interaction between Cosmic Rays and Matter

宇宙射线与物质之间的相互作用

Disintegration of Light Atomic Nuclei by the Capture of Fast Neutrons

轻核俘获快中子产生的核衰变

Extremely Low Temperatures

极低温

Recent Developments in Television

电视技术的最新进展

Production of High Magnetic Fields at Low Temperatures

低温下强磁场的产生

New Results in Cosmic Ray Measurements

宇宙射线测量中的新结果

Interaction of Hard γ -rays with Atomic Nuclei

硬 γ 射线和原子核的反应

A Suggested Explanation of β -ray Activity

β 射线放射性的一种可能的解释

Latitude Effect of Cosmic Radiation

宇宙射线的纬度效应

The Positive Electron

正电子

1934

The Ether-drift Experiment and the Determination of the Absolute Motion of the Earth

以太漂移实验和地球绝对运动的确定

Artificial Production of a New Kind of Radio-element

一种新放射性元素的人工制造

A Velocity-modulation Television System

一个基于速度调制的电视系统

The Positron

正电子

Production of Induced Radioactivity by High Velocity Protons

由高速质子产生的感生放射性

Designation of the Positive Electron

正电子的命名

Transmutation Effects Observed with Heavy Hydrogen

通过重氢观察到的嬗变效应

Supraconductivity of Films of Tin

锡膜的超导电性

Persistent Currents in Supraconductors

超导体中的持续电流

The Velocity of Light

光的速度

Attempt to Detect a Neutral Particle of Small Mass

探测小质量中性粒子的尝试

Developments of Television

电视的发展

The “Neutrino”

“中微子”

Disintegration of the Diplon

氕核的蜕变

Commercial Production of Heavy Water

重水的商业化生产

The Neutrino

中微子

Liquefaction of Helium by an Adiabatic Method without Pre-cooling with Liquid Hydrogen

无液氢预冷的绝热法氦液化

Mass of the Neutron

中子的质量

The Explanation of Supraconductivity

超导电性的解释

Modern Ideas on Nuclear Constitution

核组成的现代思想

Radioactivity Induced by Neutron Bombardment

由中子轰击引发的放射性

Production of Large Quantities of Heavy Water

重水的大量生产

Possible Production of Elements of Atomic Number Higher than 92

原子序数大于92的元素的可能生成

The Factor $\frac{137}{136}$ in Quantum Theory
量子理论中的137/136因子

Exchange Forces between Neutrons and Protons, and Fermi's Theory

质子中子之间的交换力与费米理论

Interaction of Neutrons and Protons

中子和质子的相互作用

A "Nuclear Photo-effect": Disintegration of the Diplon by γ -rays
一种“核的光效应”： γ 射线引发的氘核蜕变

1935

Quantum Mechanics and Physical Reality

量子力学和物理实在

Isotopic Constitution of Uranium

铀的同位素构成

The Fundamental Paradox of the Quantum Theory

量子理论的基本佯谬

Uncertainty Principle and the Zero-point Energy of the Harmonic Oscillator

测不准原理和谐振子的零点能

The Slowing Down of Neutrons by Collisions with Protons

与质子碰撞而导致的中子慢化

1938

Viscosity of Liquid Helium below the λ -point

液态氦在 λ 点以下的黏度

Flow of Liquid Helium II

液氦II的流动

The λ -phenomenon of Liquid Helium and the Bose-Einstein Degeneracy

液氦的 λ 现象和玻色-爱因斯坦简并

Mesotron (Intermediate Particle) as a Name for the New Particles

of Intermediate Mass

将介子（中间粒子）定为一种中间质量新粒子的名字

1939

New Broadcasting System

新的广播系统

Interpretation of Beta-disintegration Data

对 β 衰变数据的解释

Liquid Helium

液氦

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

由中子引起的铀衰变：一类新型核反应

Theory of Mesons and Nuclear Forces

介子和核力理论

Surface Transport in Liquid Helium II

液氦II中的表面传输

[返回总目录](#)

《自然》学科经典系列 (英汉对照)

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Foreword by Tsung Dao Lee

We can appreciate the significance of natural science to human life in two aspects. Materially, natural science has achieved many breakthroughs, particularly in the past hundred years or so, which have brought about revolutionary changes to human life. At the same time, the spirit of science has taken an ever-deepening root in the hearts of the people. Instead of alleging that science is omnipotent, the spirit of science emphasizes down-to-earth and scrupulous research, and critical and creative courage. More importantly, it stands for the dedication to working for the wellbeing of humankind. This is perhaps more meaningful than scientific and technological achievements themselves, which may be closely related to specific backgrounds of the times. The spirit of science, on the other hand, constitutes a most valuable and constant component of humankind's spiritual civilization.

中文

In this sense, *Nature: The Living Record of Science* presents not only the historical paths of the various fields of natural science for almost a century and a half, , but also the unremitting spirit of numerous scientists in their pursuit of truth. One of the most influential science journals in the whole world, *Nature*, reflects a general picture of different branches of science in different stages of development. It has also reported many of the most important discoveries in modern science. The collection of papers in this series includes breakthroughs such as the special theory of relativity, the maturing of quantum mechanics and the mapping of the human genome sequence. In addition, the editors have not shunned papers which were proved to be wrong after publication. Included also are the academic debates over the relevant topics. This speaks volumes of their vision and

broadmindedness. Arduous is the road of science; behind any success are countless failures unknown to outsiders. But such failures have laid the foundation for success in later times and thus should not be forgotten. The comprehensive and thoughtful coverage of these volumes will enable readers to gain a better understanding of the achievements that have tremendously promoted the progress of science and technology, the evolution of key and cutting-edge issues of the relevant fields, the inspiration brought about by academic controversies, the efforts and hardships behind these achievements, and the true meaning of the spirit of science. 中文

China now enjoys unprecedented opportunities for the development of science and technology. At the policy level, the state has created a fine environment for scientific research by formulating medium- and long-term development programs. As for science and technology, development in the past decades has built up a solid foundation of research and a rich pool of talent. Some major topics at present include how to introduce the cream of academic research from abroad, to promote Sino-foreign exchange in science and technology, to further promote the spirit of science, and to raise China's development in this respect to the advanced international level. The co-publication of *Nature: The Living Record of Science* by the Foreign Language Teaching and Research Press, Macmillan Publishers Limited and the Nature Publishing Group will prove to be a huge contribution to the country's relevant endeavors. I sincerely wish for its success.

中文

Science is a cause that does not have a finishing line, which is exactly the eternal charm of science and the source of inspiration for scientists to explore new frontiers. It is a cause worthy of our uttermost exertion. 中文

T. D. Lee

Editor's note: The foreword was originally written for the ten-volume
Nature: The Living Record of Science. [中文](#)

李政道序

如何认识自然科学对人类生活的意义，可以从两个方面来分析：一是物质层面，尤其是近百年来，自然科学取得了许多跨越性的发展，给人类生活带来了许多革命性的变化；二是精神层面，科学精神日益深入人心，这种科学精神并不是认为科学万能、科学可以解决一切问题，它应该是一种老老实实、严谨缜密、又勇于批判和创造的精神，更重要的是，它具有一种坚持为人类福祉而奋斗的信念。这种科学精神可能比物质意义上的科技成就更重要，因为技术进步的影响可能与时代具体的背景有密切关系，但科学精神却永远是人类精神文明中最可宝贵的一部分。

[英文](#)

从这个意义上，这套《〈自然〉百年科学经典》丛书的出版，不仅为读者呈现了一个多世纪以来自然科学各个领域发展的历史轨迹，更重要的是，它展现了无数科学家在追求真理的过程中艰难求索、百折不回的精神世界。《自然》作为全世界最有影响力的科学期刊之一，反映了各个学科在不同发展阶段的概貌，报道了现代科学中最重要的发现。这套丛书的可贵之处在于，它不仅汇聚了狭义相对论的提出、量子理论的成熟、人类基因组测序完成这些具有开创性和突破性的大事件、大成就，还将一些后来被证明是错误的文章囊括进来，并展现了围绕同一论题进行的学术争鸣，这是一种难得的眼光和胸怀。科学之路是艰辛的，成功背后有更多不为人知的失败，前人的失败是我们今日成功的基石，这些努力不应该被忘记。因此，《〈自然〉百年科学经典》这套丛书不但能让读者了解对人类科技进步有着巨大贡献的科学成果，以及科学中的焦点和前沿问题的演变轨迹，更能使有志于科学研究的人感受到思想激辩带来的火花和收获背后的艰苦努力，帮助他们理解科学精神的真意。

[英文](#)

当前，中国科学技术的发展面临着历史上前所未有的机遇，国家已经制定了中长期科学和技术发展纲要，为科学研究创造了良好的制度环

境，同时中国的科学技术经过多年的积累也已经具备了很好的理论和人才基础。如何进一步引进国外的学术精华，促进中外科技交流，使科学精神深入人心，使中国的科技水平迅速提升至世界前列就成为这一阶段的重要课题。因此，外语教学与研究出版社和麦克米伦出版集团合作出版这套《〈自然〉百年科学经典》丛书，对中国的科技发展可谓贡献巨大，我衷心希望这套丛书的出版获得极大成功，促进全民族的科技振兴。 英文

科学的事业永无止境。这是科学的永恒魅力所在，也是我们砥砺自身、不断求索的动力所在。这样的事业，值得我们全力以赴。 英文

李政道

编者注：此篇原为《〈自然〉百年科学经典》（十卷本）的序。 英文

Foreword by Lu Yongxiang

Since the birth of modern science, and in particular throughout the 20th century, we have continuously deepened our understanding of Nature, and developed more means and methods to make use of natural resources. Technological innovation and industrial progress have become decisive factors in promoting unprecedented development of productive forces and the progress of society, and have greatly improved the mode of production and the way we live.

中文

The 20th century witnessed many revolutions in science. The establishment and development of quantum theory and the theory of relativity have changed our concept of time and space, and have given us a unified understanding of matter and energy. They served as a theoretical foundation upon which a series of major scientific discoveries and technological inventions were made. The discovery of the structure of DNA transformed our understanding of heredity and helped to unify our vision of the biological world. As a corner-stone in biology, DNA research has exerted a far-reaching influence on modern agriculture and medicine. The development of information science has provided a theoretical basis for computer science, communication technology, intelligent manufacturing, understanding of human cognition, and even economic and social studies. The theory of continental drift and plate tectonics has had important implications for seismology, geology of ore deposits, palaeontology, and palaeoclimatology. New understandings about the cosmos have enabled us to know in general terms, and also in many details, how elementary particles and chemical elements were formed, and how this led to the formation of molecules and the appearance of life, and

even the origin and evolution of the entire universe.

[中文](#)

The 20th century also witnessed revolutions in technology. Breakthroughs in fundamental research, coupled to the stimulus of market forces, have led to unparalleled technological achievements. Energy, materials, information, aviation and aeronautics, and biological medicine have undergone dramatic changes. Specifically, new energy technologies have helped to promote social development; new materials technologies promote the growth of manufacturing and industrial prosperity; information technology has ushered in the Internet and the pervasive role of computing; aviation and aeronautical technology has broadened our vision and mobility, and has ultimately led to the exploration of the universe beyond our planet; and improvements in medical and biological technology have enabled people to live much better, healthier lives.

[中文](#)

Outstanding achievements in science and technology made in China during its long history have contributed to the survival, development and continuation of the Chinese nation. The country remained ahead of Europe for several hundred years before the 15th century. As Joseph Needham's studies demonstrated, a great many discoveries and innovations in understanding or practical capability—from the shape of snowflakes to the art of cartography, the circulation of the blood, the invention of paper and sericulture and, most famously, of compasses and gunpowder—were first made in China. The Four Great Inventions in ancient China have influenced the development process of the world. Ancient Chinese astronomical records are still used today by astronomers seeking to understand astrophysical phenomena. Thus Chinese as well as other long-standing civilizations in the world deserve to be credited as important sources of modern science and technology.

[中文](#)

Scientific and technological revolutions in 17th and 18th century Europe, the First and Second Industrial Revolutions in the 18th and

19th centuries, and the spread of modern science education and knowledge sped up the modernization process of the West. During these centuries, China lagged behind. [中文](#)

Defeat in the Opium War (1840—1842) served as strong warning to the ancient Chinese empire. Around and after the time of the launch of *Nature* in 1869, elite intellectuals in China had come to see the importance that science and technology had towards the country's development. Many scholars went to study in Western higher education and research institutions, and some made outstanding contributions to science. Many students who had completed their studies and research in the West returned to China, and their work, together with that of home colleagues, laid the foundation for the development of modern science and technology in the country. [中文](#)

In the six decades since the founding of the People's Republic of China, the country has made a series of achievements in science and technology. Chinese scientists independently developed the atomic bomb, the hydrogen bomb and artificial satellite within a short period of time. The continental oil generation theory led to the discovery of the Daqing oil field in the northeast. Chinese scientists also succeeded in synthesizing bovine insulin, the first protein to be made by synthetic chemical methods. The development and popularization of hybrid rice strains have significantly increased the yields from rice cultivation, benefiting hundreds of millions of people across the world. Breakthroughs in many other fields, such as materials science, aeronautics and life science, all represent China's progress in modern science and technology. [中文](#)

As the Chinese economy continues to enjoy rapid growth, scientific research is also producing increasing results. Many of these important results have been published in first-class international science journals such as *Nature*. This has expanded the influence of Chinese science

research, and promoted exchange and cooperation between Chinese scientists with colleagues in other countries. All these indicate that China has become a significant global force in science and technology and that greater progress is expected in the future. [中文](#)

Science journals, which developed alongside modern science, play an essential role in faithfully recording the path of science, as well as spreading and promoting modern science. Such journals report academic development in a timely manner, provide a platform for scientists to exchange ideas and methods, , explore the future direction of science, stimulate academic debates, promote academic prosperity, and help the public to better understand science. While promoting science and technology, China should place greater emphasis on the betterment of science journals. We should draw on the philosophies and methods of leading science journals such as *Nature*, improve the standards of digital access, and enable some of our own science journals to extend their impact beyond China in the not too distant future so that they can serve as an advanced platform for the development of science and technology in our country. [中文](#)

In the 20th century, *Nature* published many remarkable discoveries in disciplines such as biology, geoscience, environmental science, materials science, and physics. The selection and publication of the best of the more than 100,000 articles in *Nature* over the past 150 years or so in English-Chinese bilingual format is a highly meaningful joint undertaking by the Foreign Language Teaching and Research Press, Macmillan Publishers Limited and the Nature Publishing Group. I believe that *Nature: The Living Record of Science* will help bridge cultural differences, promote international cooperation in science and technology, prove to be high-standard readings for its intended large audience, and play a positive role in improving scientific and technological research in our country. I fully endorse and support the

project. 中文

The volumes offer a picture of the course of science for nearly 150 years, from which we can explore how science develops, draw inspiration for new ideas and wisdom, and learn from the unremitting spirit of scientists in research. Reading these articles is like vicariously experiencing the great discoveries by scientific giants in the past, which will enable us to see wider, think deeper, work better, and aim higher. I believe this collection will also help interested readers from other walks of life to gain a better understanding of and care more about science, thus increasing their respect for and confidence in science. 中文

I should like to take this opportunity to express my appreciation for the vision and joint efforts of Foreign Language Teaching and Research Press, Macmillan Publishers Limited and the Nature Publishing Group in bringing forth this monumental work, and my thanks to all the translators, reviewers and editors for their exertions in maintaining its high quality. 中文



President of Chinese Academy of Sciences

Editor's note: The foreword was originally written for the ten-volume *Nature: The Living Record of Science*. 中文

路甬祥序

自近代科学诞生以来，特别是20世纪以来，随着人类对自然的认识不断加深，随着人类利用自然资源的手段与方法不断丰富，技术创新、产业进步已成为推动生产力空前发展和人类社会进步的决定性因素，极大地改变了人类的生产与生活方式，使人类社会发生了显著的变化。

英文

20世纪是科学革命的世纪。量子理论和相对论的创立与发展，改变了人类的时空观和对物质与能量统一性的认识，成为了20世纪一系列重大科学发现和技术发明的理论基石；DNA双螺旋结构模型的建立，标志着人类在揭示生命遗传奥秘方面迈出了具有里程碑意义的一步，奠定了生物技术的基础，对现代农业和医学的发展产生了深远影响；信息科学的发展为计算机科学、通信技术、智能制造提供了知识源泉，并为人类认知、经济学和社会学研究等提供了理论基础；大陆漂移学说和板块构造理论，对地震学、矿床学、古生物地质学、古气候学具有重要的指导作用；新的宇宙演化观念的建立为人们勾画出了基本粒子和化学元素的产生、分子的形成和生命的出现，乃至整个宇宙的起源和演化的图景。

英文

20世纪也是技术革命的世纪。基础研究的重大突破和市场的强劲拉动，使人类在技术领域获得了前所未有的成就，能源、材料、信息、航空航天、生物医学等领域发生了全新变化。新能源技术为人类社会的发展提供了多元化的动力；新材料技术为人类生活和科技进步提供了丰富的物质材料基础，推动了制造业的发展和工业的繁荣；信息技术使人类迈入了信息和网络时代；航空航天技术拓展了人类的活动空间和视野；医学与生物技术的进展极大地提高了人类的生活质量和健康水平。

英文

历史上，中国曾经创造出辉煌的科学技术，支撑了中华民族的生存、发展和延续。在15世纪之前的数百年里，中国的科技水平曾遥遥领

先于欧洲。李约瑟博士曾经指出，从雪花的形状到绘图的艺术、血液循环、造纸、养蚕，包括更有名的指南针和火药，都是首先由中国人发现或发明的。中国的“四大发明”影响了世界的发展进程，古代中国的天文记录至今仍为天文学家在研究天体物理现象时所使用。中华文明同其他悠久的人类文明一样，成为了近代科学技术的重要源泉。 [英文](#)

但我们也要清醒地看到，发生在17~18世纪欧洲的科学革命、18~19世纪的第一次和第二次工业革命，以及现代科学教育与知识的传播，加快了西方现代化的进程，同时也拉大了中国与西方的差距。 [英文](#)

鸦片战争的失败给古老的中华帝国敲响了警钟。就在《自然》创刊前后，中国的一批精英分子看到了科学技术对于国家发展的重要性，一批批中国学子到西方高校及研究机构学习，其中一些人在科学领域作出了杰出的贡献。同时，一大批留学生回国，同国内的知识分子一道，为现代科学技术在中国的发展奠定了基础。 [英文](#)

新中国成立60年来，中国在科学技术方面取得了一系列成就。在很短的时间里，独立自主地研制出“两弹一星”；在陆相生油理论指导下，发现了大庆油田；成功合成了牛胰岛素，这是世界上第一个通过化学方法人工合成的蛋白质；杂交水稻研发及其品种的普及，显著提高了水稻产量，造福了全世界几亿人。中国人在材料科学、航天、生命科学等许多领域，也取得了一批重要成果。这些都展现了中国在现代科技领域所取得的巨大进步。 [英文](#)

当前，中国经济持续快速增长，科研产出日益增加，中国的许多重要成果已经发表在像《自然》这样的世界一流的科技期刊上，扩大了中国科学研究的影响，推动了中国科学家和国外同行的交流与合作。现在，中国已成为世界重要的科技力量。可以预见，在未来，中国将在科学和技术方面取得更大的进步。 [英文](#)

伴随着现代科学产生的科技期刊，忠实地记录了科学发展的轨迹，在传播和促进现代科学的发展方面发挥了重要的作用。科技期刊及时地报道学术进展，交流科学思想和方法，探讨未来发展方向，以带动学术争鸣与繁荣，促进公众对科学的理解。中国在推动科技进步的同时，应更加重视科技期刊的发展，学习包括《自然》在内的世界先进科技期刊

的办刊理念和方法，提高期刊的数字化水平，使中国的一些科技期刊早日具备世界影响力，为中国科学技术的发展创建高水平的平台。 英文

文

20世纪的生物学、地球科学、环境科学、材料科学和物理学等领域的许多重大发现，都被记录在《自然》上。外语教学与研究出版社、麦克米伦出版集团和自然出版集团携手合作，从《自然》创刊近一百五十年来发表过的十万余篇论文中撷取精华，并译成中文，以双语的形式呈现，纂为《〈自然〉百年科学经典》丛书。我认为这是一项很有意义的工作，并相信本套丛书的出版将跨越不同的文化，促进国际间的科技交流，向广大中国读者提供高水平的科学技术知识文献，为提升我国科学技术研发水平发挥积极的作用。我赞成并积极支持此项工作。 英文

丛书将带领我们回顾近一百五十年来科学的发展历程，从中探索科学发展的规律，寻求思想和智慧的启迪，感受科学家们百折不挠的钻研精神。阅读这套丛书，读者可以重温科学史上一些科学巨匠作出重大科学发现的历程，拓宽视野，拓展思路，提升科研能力，提高科学道德。我相信，这套丛书一定能成为社会各界的良师益友，增强他们对科学的了解与热情，加深他们对科学的尊重与信心。 英文

借此机会向外语教学与研究出版社、麦克米伦出版集团、自然出版集团策划出版本丛书的眼光和魄力表示赞赏，对翻译者、审校者和编辑者为保证丛书质量付出的辛勤劳动表示感谢。

是为序。 英文



中国科学院院长

编者注：此篇原为《〈自然〉百年科学经典》（十卷本）的序。 英文

文

Foreword by Philip Ball

The papers in these two volumes are drawn from the selection that appeared in *Nature: The Living Record of Science*, a multi-volume compilation of the most important contributions to the international science journal *Nature* from 1869, when it began, until 2007. Progress in Physics collects together the papers specifically in the discipline of physics, ranging from the theoretical foundations of the discipline to astronomy and applications in areas such as semiconductor microelectronics. *Nature* has had a particularly strong tradition of publishing in this field; in the early part of the twentieth century especially, it was the regular journal of choice for physicists presenting their new discoveries. This selection therefore offers a picture of how physics has changed from the era of James Clerk Maxwell and Lord Kelvin to today. These papers are made readily accessible here to readers in China for the first time by simultaneous publication in English and in Mandarin Chinese, as well as being accompanied by short introductions that explain the context and implications of the work described. [中文](#)

When *Nature* began, physics was still relatively new as a recognized discipline. Of course, what we now regard as physics has a much longer history. Aristotle's wide-ranging treatise on the natural world in the 4th century BCE is simply given that one-word title today, and the studies of the laws of motion by Galileo and Isaac Newton in the seventeenth century sit at the heart of the so-called Scientific Revolution. In a sense, one might argue that it was the character of physics as the foundation for all natural philosophy that delayed for so long its being recognized as a distinct discipline: physics seems to be about everything. It is often noted that the laws governing the

interactions of atoms and fundamental particles are ultimately responsible for all of chemistry and biology, and that physical law also defines and constrains our view of the entire cosmos and how it has evolved since the universe began 13.8 billion years ago. [中文](#)

But the recognition that physics needs to be both pursued as a distinct fundamental and experimental science, and that its applications are central to the development of socially transformative technologies, was reflected in the inauguration, just a few years after *Nature* began, of the Cavendish Laboratory at the University of Cambridge—which, with Maxwell as its first director, quickly became and has remained one of the most important centres of academic study in the discipline. Maxwell's kinetic theory of gases was presented and discussed in the journal in 1873. [中文](#)

In the late nineteenth century, some of the important contributions to physics in *Nature* concerned questions in astronomy: from where, for example, do stars like the sun get their enormous, seemingly inexhaustible energy? It was only through the discoveries in fundamental physics—the identification of X-rays in 1895 and then, very soon after, of radioactivity—that an answer to this question began to emerge, via the discovery of the energy residing in the atomic nucleus. And the particles emitted by radioactive decay could be used to probe the internal structure of atoms themselves, leading to a rationalization of the properties of the chemical elements as well as to the invention of the first of the devices—particle accelerators—that today supply the principal tools for exploring the laws that govern the properties and composition of matter at scales far smaller than those of atoms. [中文](#)

That we needed to understand the atomic nucleus before we could understand the sun is a perfect illustration of the unity that physics often reveals. It is now clear that understanding the cosmos at the grandest scales requires deeper theoretical insight into its constitution

at the smallest. In fact, a unification of the theories that provide the conceptual frameworks at the former and the latter scales—general relativity and quantum mechanics, both of which developed in the early twentieth century (and both being discussed in *Nature* at that time)—now represents one of the most important goals in physics.

[中文](#)

It is sometimes said that physics was the foremost science of the first half of the twentieth century, while biology claimed that role in the second half. But much of the current understanding in the life sciences has been, and continues to be, dependent on advances in physics. X-rays become the primary tool for probing the structure of proteins and other biomolecules, most notably revealing the chemical nature of DNA in 1953. Measuring signals from magnetic atomic nuclei in the technique of nuclear magnetic resonance has also been vital for studying the structure of biological matter. The use of this technique for imaging, reported in *Nature* in 1973 and rewarded with a Nobel prize, is now essential for advances in neuroscience and for biomedical research and clinical medicine. [中文](#)

Nature followed closely developments in the application of physics, not least in telecommunications technologies such as the telephone and television. The equivalent today is the application of physics to microelectronics, leading first to digital solid-state integrated circuits and computers and now to the implementation of quantum-mechanical rules of information processing in quantum computing and cryptography. Information technology and artificial intelligence look sure to become one of the most transformative physics-based technologies of the twenty-first century. [中文](#)

Well before achieving its current global prominence, China established a solid presence in physics. Chen-Ning Yang and Tsung-Dao Lee won the 1957 Nobel prize in physics for showing theoretically how the conservation principle governing the property of parity—a kind of

symmetry exhibited by fundamental particles—could be violated. They proposed an experiment for testing their ideas using nuclear physics, specifically by looking at the particles emitted in a radioactive decay process. This experiment was conducted in 1956 by Chinese-born physicist Chien-Shiung Wu, and it was her success in verifying Lee and Yang's predictions that opened the door for their Nobel prize. If it were being awarded today, Wu would surely have shared it. [中文](#)

Among the more recent Chinese-born Nobel laureates is Daniel Chee Tsui, whose award in 1998 recognized his work in identifying a fundamental quantum-mechanical effect in semiconductor microstructures. That blend of quantum fundamentals and device engineering, with potentially powerful applications, is found too in the work in China today on quantum information technologies, an area in which Chinese scientists have become world leaders. The Micius satellite, launched in 2016 and operated by the Chinese Academy of Sciences, is the first of its kind dedicated to the transmission of quantum-encrypted data for secure telecommunications, and is a key component of the project Quantum Experiments at Space Scale (QUESS). [中文](#)

This collection of physics papers from *Nature* will be valuable for physicists both in academia and industry, and for science historians. The short editorial introductions will also help to make the papers accessible to and useful for students of physics, as well as to more general audiences. It is a necessarily incomplete sample of physics in from the mid-nineteenth to the early twenty-first centuries, but we hope that the selection of papers here will contain something to satisfy and interest all tastes. It includes papers of historical interest as well as those whose conclusions remain relevant to the subject today. What emerges, we hope, is more than a record of a discipline; it is a portrait of the development of some of the most profound ideas in intellectual

global culture over the past 150 years.

中文

A handwritten signature in black ink, consisting of stylized, cursive letters that appear to be 'M. S.' or similar.

Former Consultant Editor for *Nature*

菲利普·鲍尔序

《〈自然〉百年物理经典》（共两册）的文章皆出自十卷本论文精选集《〈自然〉百年科学经典》，后者收录了国际学术期刊《自然》自1869年创刊至2007年发表过的最具影响力的经典文献。《〈自然〉百年物理经典》以物理学为线索，收录了从基础理论物理到天文学和半导体微电子学等应用物理方向的文章。在学术出版领域，物理学是《自然》的传统优势学科，特别是在二十世纪早期，物理学家更是倾向于将自己的最新成果发表在《自然》上。《〈自然〉百年物理经典》展现了物理学从詹姆斯·克拉克·麦克斯韦和开尔文勋爵时代发展至今的光辉历程。这些经典文献首次以中英对照的形式出版，每篇同时配有简短的导读，以便中国读者快速了解文献的内容和研究的意义。 [英文](#)

《自然》创刊伊始，物理学作为独立的学科，尚处于起步阶段。诚然，如今人们所说的物理学有着更为悠久的历史。公元前四世纪，亚里士多德便为自己的一部论述自然界万物的著作冠以了“物理学”之名。十七世纪，伽利略和艾萨克·牛顿对于物体运动法则的研究，也成为后世所说的科学革命的核心所在。在某种意义上，人们或许可以说，物理是一切自然哲学之基础。正是这一特征，使得物理长久以来未能被人们确立为一门独立的学科：似乎世间万物之道皆归于物理。我们经常可以发现，支配原子和基本粒子相互作用的定律同样适用于化学和生物学，而物理学定律也定义和约束了我们对整个宇宙的理解，以及自138亿年前宇宙诞生以来它是如何演化的。 [英文](#)

物理学的研究应该从理论基础和实验观察两个方面着手，同时，其应用对于社会的革命性技术的发展也起到了至关重要的作用。上述两点认识在剑桥大学卡文迪什实验室的创立（《自然》创刊几年之后）中得到了印证。麦克斯韦担任实验室的首位主任，之后实验室迅速成长为世界上最重要的物理学学术研究中心之一。1873年，《自然》上就曾刊发并讨论过麦克斯韦的气体动力学理论。 [英文](#)

十九世纪末，《自然》上刊发了多篇重要论文，所涉及的问题也是天文学关心的问题：例如，太阳那样的恒星是从哪里获得巨大的且看似无穷无尽的能量的？回答上述问题有赖于基础物理学的相关发现——1895年X射线的发现及紧随其后放射性的发现，以及随后关于原子核内能量的研究。放射性衰变放出的粒子可用来探究原子自身的内部结构，从而使化学元素的性质得到合理化的解释，并使得粒子加速器等设备的建造得以实现。今天，粒子加速器是探索远小于原子尺度的物质的性质和构成规律的主要实验设备。 [英文](#)

了解太阳之前需要先了解原子核，这很好地阐释了物理学中经常揭示的统一性。在极大尺度上理解宇宙需要在极小尺度上对其构成有更为深入的理论研究，这点现在已经很清楚。事实上，为极大尺度和极小尺度分别提供了概念框架的理论——广义相对论和量子力学——都是在二十世纪初被提出的（当时也在《自然》上引发了讨论），而统一上述两种理论现已成为物理学最重要的目标之一。 [英文](#)

有时，人们会说二十世纪前半叶是物理学取得空前发展的时代，二十世纪后半叶是生物学蓬勃兴起的时代。但关于生命科学的很多理解都曾经是，也一直是基于物理学的进展。X射线成为测定蛋白质结构和其他生物分子结构的主要技术，最著名的发现是在1953年揭示了DNA的化学本质。利用核磁共振技术测量来自磁性原子核的信号也是研究生物物质结构非常重要的方法。1973年发表在《自然》上的关于利用该技术进行成像分析的研究工作之后也获得了诺贝尔奖，核磁共振成像现已成为神经科学、生物医学和临床医学研究必不可少的手段。 [英文](#)

《自然》也密切跟踪物理学在实际应用领域的最新进展，其中最为著名的当属电话、电视等电信技术。当今物理学的应用领域主要集中在微电子学：从数字固态集成电路和计算机的实现，到如今在量子计算和量子密码学领域内基于量子力学基本原理对信息进行处理。植根于物理学的信息技术和人工智能似乎正在成长为引领二十一世纪技术变革的中坚力量。 [英文](#)

中国在各行各业取得了举世瞩目的辉煌成就，在物理学领域亦打下了坚实的基础。杨振宁和李政道从理论上推翻了宇称守恒定律从而荣获

1957年的诺贝尔物理学奖，宇称是基本粒子表现出来的一种对称性。他们提出了通过核物理的实验，具体来说即通过观察放射性衰变过程中释放出来的粒子来验证他们的理论。这个实验于1956年由华裔女科学家吴健雄领导完成，她成功验证了李政道和杨振宁的设想，从而帮助两人成功斩获诺贝尔奖。现在回首这段历史，吴健雄无疑也应该分享这一荣誉。

[英文](#)

华裔科学家崔琦因发现半导体微结构中的基本量子力学效应（分数量子霍尔效应）而荣获1998年诺贝尔物理学奖。今天，中国的量子信息技术研究融合了量子原理和器件工程学，具有无限的应用潜力，这也是一个中国科学研究领先世界水平的领域。由中国科学院联合研究团队研制的“墨子号”量子卫星于2016年成功发射，这是首颗用于传输量子加密数据以实现安全通信的卫星，也是中国空间尺度量子实验项目（QUESS）的核心部分。

[英文](#)

这套《自然》杂志物理论文选集的出版，无论对学术界和产业界的物理学家，抑或是科学史研究人员，都极具参考价值。简短的编辑导读也会帮助物理专业的学生及大众读者更好地理解 and 运用这些经典文献。这套选集或许并不能完整地呈现二十世纪中期至二十一世纪初所有物理学研究成果，但我们仍期望各位读者能从中找到自己喜欢并感兴趣的内容。为此，这套选集不仅收录了那些具有历史价值的文献，同时也收录了那些研究结论至今仍具有重要意义的文章。我们希望，呈现在诸位面前的，不仅仅是一部物理学的编年史，更是一幅荟萃过去150年全人类智慧文明中最为深刻思想的灿烂画卷。

[英文](#)

菲利普·鲍尔
《自然》前任顾问编辑

Volume I

The Atomic Controversy

In 1869, the atomic hypothesis of the constitution of matter, as proposed 60 years earlier by the Englishman John Dalton, had yet to receive definitive confirmation. This short essay reviews arguments for and against the atomic hypothesis which, as Dalton had pointed out, lends order to many otherwise puzzling phenomena. It can explain the law of definite proportion: the fact that chemical compounds always involve elements in simple rational proportions. And the hypothesis had been shown to explain why atomic elements in the gaseous state all had similar heat capacities (dependence of temperature on heat input). Even so, the essay concludes that such arguments for atomism remained circumstantial. [中文](#)

IT is one of the most remarkable circumstances in the history of men, that they should in all times have sought the solution of human problems in the heavens rather than upon the earth. Sixty years ago a memorable instance of this truth occurred when Dalton borrowed from the stars an explanation of the fundamental phenomena of chemical combination. Carbon and oxygen unite in a certain proportion to form “carbonic acid”; and this proportion is found to be invariable, no matter from what source the compound may have been prepared. But carbon and oxygen form one other combination, namely, “carbonic oxide”—the gas whose delicate blue flame we often see in our fires. Carbonic oxide may be obtained from many sources; but, like carbonic acid, its composition is always exactly the same.

These two bodies, then, illustrate the law of *Definite* Proportions. But Dalton went a step further. He found that, for the same weight of carbon, the amount of oxygen in “carbonic acid” was *double* that which exists in carbonic oxide. Several similar instances were found of two elements forming compounds in which, while the weight of the one remained constant, the other doubled, trebled, or quadrupled itself. Hence the law of *Multiple* Proportions. The question was—in fact, the question is—how to account for these laws. Dalton soon persuaded himself that matter was made up of very small particles or *minima naturae*, not by any possibility to be reduced to a smaller magnitude. Matter could not be divisible without limit; there must be a barrier somewhere. No doubt, as a chemist, he would have rejected the famous couplet—

Big fleas have little fleas, upon their backs, to bite 'em;
And little fleas have smaller fleas, and so *ad infinitum*.

“Let the divisions be ever so minute,” he said, “the number of particles must be finite; just as in a given space of the universe, the number of stars and planets cannot be infinite. We might as well attempt to introduce a new planet into the solar system, or to annihilate one already in existence, as to create or destroy a particle of hydrogen.” All substances, then, are composed of atoms; and these attract each other, but at the same time keep their distance, just as is the case with the heavenly bodies. The atoms of one compound do not resemble those of another in weight, or size, or mutually gravitating power. But as they are indivisible, it is between them that we must conceive all chemical action to take place; and an atom of any particular kind must always have the same weight. The atom of carbon weighs 5; the atom of oxygen weighs 7. Carbonic oxide, containing one of each must therefore be invariably constituted of 5 carbon, and 7 oxygen: carbonic acid must in like manner contain 5 carbon, and 14 oxygen. Here, then, Dalton not only states that he has accounted for the two

laws we have mentioned by making a single assumption; but he evidently intends his theory to be used as a criterion or control in all future analytical results, and already views it as the birth-place of chemical enterprise. [中文](#)

Such, and so great, was the atomic theory of Dalton; founded, certainly, on erroneous numbers, but containing in itself the germ of their correction; aspiring to the command in innumerable conquests; and setting itself for the rise or fall of the chemical spirit. [中文](#)

It is hardly necessary to make any detailed review of the history of the atomic theory. Berzelius made it a starting-point for researches which, on the whole, have been unsurpassed in their practical importance, and engrafted upon it his celebrated electrical doctrine. Davy and Faraday refused to admit it; Laurent and Gerhardt accepted it doubtfully, or in a much modified form. Henry declared that it did not rest on an inductive basis. There can be no doubt, however, that the atomic theory has been accepted by the majority of chemists, as may be seen on even a cursory inspection of the current literature of their science. Our present intention is to give such a summary of the atomic question as may be serviceable to those who take an interest in the discussion at the Chemical Society on Thursday last. [中文](#)

The modern supporters of the atomic theory agree with Dalton in the fundamental suppositions we have given above; but assert that they have a much stronger case. The phenomena of gaseous combination and specific heat have indeed changed the numerical aspect of the theory, but not its substance. The simplicity of all the results we have accumulated with respect to combining proportions is itself a great argument for the existence of atoms. They all, for example, have the same capacity for heat; they all, when in the gaseous state, have a volume which is an even multiple of that of one part by weight of hydrogen. But bodies in the free or uncombined state—such, in fact, as we see them—more commonly consist of many clusters of atoms

(*molecules*) than of simple atoms. These molecules are determined by the fact that when in the gaseous state they all have the same volume. Again, select a series of chemical equations, in which water is formed, and eliminate between them so as to obtain the smallest proportion of water, taking part in the transformations they represent. It will be found that the number is 18; which necessarily involves the supposition that the oxygen (16) in water (18) is an indivisible quantity. To put this last point another way: hydrochloric acid, if treated with soda, no matter in what amount, only forms one compound (common salt). Now we know that the action in this case consists in the exchange of hydrogen for sodium. But if hydrogen were infinitely divisible, we ought to be able to effect an inexhaustible number of such exchanges, and produce an interminable variety of compounds of hydrogen, sodium, and chlorine; hydrochloric acid being the limit on the one side, and common salt (sodic chloride) terminating the other. No such phenomenon occurs; and, since matter must be infinitely or finitely divisible, and has been thus proved not to be the former, it must be the latter. Atoms, therefore, really exist; and chemical combination is inconsistent with any other supposition. Those who hold the contrary opinion are bound to produce an alternative theory, which shall explain the facts in some better way.

中文

Now let us hear the plaintiff in reply. 中文

The atomic theory has undoubtedly been of great service to science, since the laws of definite and multiple proportions would probably not have received the attention they deserve, but for being stated in terms of that theory. Yet we must discriminate between these laws, which are the simple expression of experimental facts, and the assumption of atoms, which preceded them historically, and therefore has no necessary connection with them. For it was the Greek atomic theory which Dalton revived. Nor has any substance yet been produced by

the atomists, which we cannot find means to divide. If, moreover, we have no alternative but to admit the infinite divisibility of matter, even that is consistent with the simple ratios in which bodies combine; for two or more infinities may have a finite ratio. Therefore, the observed simplicity, if used as an argument, cuts both ways. Possibly we are mistaken in connecting the ideas of matter and division at all; at any rate, the connection has never been justified by the opposite side. Again, admitting the argument based on the formation of common salt, the atomic theory does not tell us why only one third of the hydrogen in tartaric acid can be exchanged for sodium; why, indeed, only a fraction of the hydrogen in most organic substances can be so exchanged. Yet, the explanation of the one fact, when discovered, will evidently include that of the other. On the whole, it appears that the atomic theory demands from us a belief in the existence of a limit to division. No such limit has been exhibited to our senses; and the facts themselves do not raise the idea of a limit, which Dalton really borrowed from philosophy. The apparent simplicity of chemical union we do not profess to explain, but to be waiting for any experimental interpretation that may arise. The atomists, in bringing forward their theory, are bound to establish it, and with them lies the *onus probandi*. 中文

The above are a few broad outlines of the existing aspect of the atomic controversy, and may somewhat assist in forming an estimate of it. The general theoretical tone of the discussion last Thursday must have surprised most who were present. Our own position is necessarily an impartial one; but it will probably be agreed that between the contending parties there is a gulf, deeper and wider than at first appears, and perhaps unprovided with a bridge. 中文

原子论战

1869年，关于物质组成的原子理论仍旧没有得到确定性的验证，尽管这一理论已经由英国人约翰·道尔顿提出达60年之久。这篇短文综述了人们对原子理论的各种支持意见和反对意见。正如道尔顿当初说的，原子理论揭示了许多分散的、令人困惑的现象背后的规律。原子理论可以解释定比定律（自然界所有化合物中的各种组成元素之间总是存在简单的比例），通过原子理论也可以解释为什么各种元素在气态时都具有相似的比热容（温度变化对于供热的依赖程度）。不过，本文最后还是认为，关于原子理论的这些论述都只是描述性的，尚未得到证实。 [英文](#)

人类历史上最值得注意的情况就是，我们在任何时候都应该从天空而不是从大地去探求人类问题的解决之道。60年前发生了一件证实这个真理的令人难忘的事例，道尔顿先生藉由恒星获得灵感，解释了化合物组成的基本现象。碳和氧以一定的比例结合形成“碳酸”，不管是用什么原料来制备碳酸这种化合物，其中碳和氧的比例都是恒定不变的。但是碳和氧还能形成另一种叫作“一氧化碳”的化合物，这种气体的火焰是蓝色的，就像我们经常的火中见到的那样。尽管一氧化碳来源广泛，但和碳酸一样，不同来源的一氧化碳在组成上总是完全相同的。这两个例子说明了什么是定比定律。但是道尔顿的研究更进了一步，他发现对于一定质量的碳，“碳酸”中氧的量是一氧化碳中的两倍。还有几个类似的例子，由两种元素组成的多种化合物，当其中一种元素的质量一定时，另外一种元素的量可能相差一倍、两倍甚至三倍，于是道尔顿提出了倍比定律。实际上，问题在于如何解释这些定律。他很快作出猜测：物质是由很小的颗粒或者不可再分的微粒组成的，这些颗粒不能再被分解成更小尺度的颗粒。物质不能被无限分割，肯定存在某种界限。作为一名化学家，他应该会批判下面这首著名的小诗：

大蚤生小蚤，蝇蝇啮其背；
小蚤复微蚤，夫何有止归。

他说：“即使分割得非常小，微粒的数目也一定是有限的，就像在一定的宇宙空间内行星和恒星的数目是有限的一样。我们可以试图向太阳系中引入一颗新的行星，或者毁掉其中一颗已存在的行星，同样地，我们也可以创造或剔除一个氢粒子。”所有的物质都是由原子构成的，这些原子就像天体一样相互吸引而又保持一定的距离。不同化合物中原子的质量、大小以及相互间的引力是不同的。但因为原子是不可再分的，所以我们必须设想所有的化学反应发生在原子之间，并且一种特定原子的质量是不变的。假设碳原子的质量是5，氧原子的质量是7。一氧化碳分子包含一个碳原子和一个氧原子，因此，它的质量肯定恒定为一个碳（5）与一个氧（7）之和。同理，碳酸分子的质量一定为一个碳（5）与两个氧（14）之和。由此，道尔顿通过一个简单的假设解释了前面提到的两个定律，同时，他显然还希望他的理论被当作将来所有分析结果的标准或参照，并且他已把这视为化学工业的起源。 [英文](#)

这就是道尔顿伟大的原子论。虽然它建立在错误的数据之上，但其中包含了正确理论的萌芽。它立志征服无数的困难，引领化学精神的荣衰。 [英文](#)

我们就不去回顾原子论的历史细节了。伯齐利厄斯以原子论为起点进行了研究，总体上来说，他的这些研究的应用价值还未被超越，他还在原子论的基础上衍生出了著名的电子学说。戴维和法拉第拒绝接受原子论。洛朗和凯哈德则半信半疑，确切地说是认可经过了很大修正后的原子论。亨利则声称原子论并非建立在归纳学的基础之上。然而，毫无疑问原子论已被大部分科学家接受，这只要大致浏览一下目前这方面的科学文献就知道了。这里我们简单总结一下关于原子论的探讨，以供那些对上周四化学学会举行的讨论感兴趣的读者参考。 [英文](#)

原子论的现代支持者同意前面所述的道尔顿的基本假设，同时他们声称拥有说服力更强的证据。气体化合现象和比热方面的研究确实改变了原子论的数值形式，但并没有改变其本质。我们积累的有关化合比例的所有结果都非常简单，这本身就是原子存在的强力论据。例如，它们

都具有同样的热容；处于气态时它们的体积都是单位质量氢气体积的偶数倍。但实际上，就像我们看到的，游离态或非化合态的物质在大多数情况下是由许多原子团（分子）而非单个原子组成。实验表明，处于气态时它们具有相同的体积，这就证明了分子的存在。再者，我们挑选一些有水生成的化学方程式，通过比较、消约可以推算出水的最小组分，我们发现其分子量是18。根据这一结果，很自然地可以推测：氧（16）在水（18）中是个不可分割的量。另外一个例子也能够说明这个观点：如果向盐酸中加入苏打，无论苏打的用量是多少，反应都只能产生一种化合物（食盐）。现在我们知道这个例子中发生的反应就是氢被钠替换了。但如果假设氢是无限可分的话，那么通过控制用量应该能够产生多种多样的交换，从而产生无数种由氢、氯、钠形成的化合物，盐酸只是反应这一侧的终点，食盐（氯化钠）是另一侧的终点。可是这种现象从来都没有发生过。可以肯定，物质要么是无限可分的要么是有限可分的，既然现在已经证明不是前者，那么必然只能是后者了。因此，可以肯定原子是确实存在的，并且化合反应的结果与其他任何假设都是不相吻合的。那些持有相反意见的人，必须提出另一种可以更好地解释这些现象的理论。 [英文](#)

现在让我们听听反对者的意见。 [英文](#)

毫无疑问原子论对科学是极有帮助的，因为如果不是用原子论的形式表述出来，倍比定律和定比定律的法则恐怕就不会受到应得的重视。但是，我们必须将这两大法则与原子假设加以区分，前者是对实验事实的简单描述，而后者在历史上先于两大法则出现，因此它们之间并无必然联系。道尔顿接受的只是古希腊的原子论而已。原子论者从来都没有得到过无法分割的物质。再者，如果我们别无选择而只能承认物质的无限可分性的话，那么这与物质化合中的简单比例也是相符合的，因为两种或两种以上的无限可分物之间也可以有一个有限的确定的比例。因此，就化合过程中观察到的简单比例来说，两种理论都能解释。很可能，我们把物质和分割这两个概念联系起来本身就是完全错误的。至少从来没有证明这种联系的正确性。另外，原子论虽然能够解释食盐形成的现象，但它并未告诉我们为什么酒石酸中只有三分之一的氢可以与钠交换，还有为什么大多数有机物中只有一部分氢可以这样交换。作为一

种正确的理论，不但要能解释已经发现的某种现象，同样也要能够解释其他的现象。总体来说，原子论似乎就是要求我们坚信存在分割的极限，但我们从来没有感到过这种极限的存在，事实本身也并没有使人们想到极限这一概念。可以说，道尔顿只是从哲学那里借来了分割的极限这个想法。我们并未声称已经解释了化学结合过程中明显的简单比例，这要等待可能出现的实验性的解释。原子论者自从提出他们理论的那天起就背负着提供证据的责任，他们必须证实这一理论。 [英文](#)

上面概述了目前原子论战的各方的观点，可能会有助于人们形成自己对原子论的评价。上周四的讨论中众人的观点可能使一些与会人员受惊了。我们的立场必须保持中立，但是有一点大家达成了共识，就是在论战双方之间存在着一条鸿沟，它比刚出现时更深、更宽，或许根本无法架通。 [英文](#)

（高如丽 翻译；汪长征 审稿）

Mathematical and Physical Science

J. C. Maxwell

James Clerk Maxwell, probably the most perceptive physical scientist in the second half of the nineteenth century, was president of the physics section of the British Association for the Advancement of Science in 1870. His presidential address, he explained, was stimulated by the previous year's address by the mathematician J. J. Cayley. It dealt with the role of molecules in the explanation of physical phenomena.

中文

The president delivered the following address:—

At several of the recent meetings of the British Association the varied and important business of the Mathematical and Physical Section has been introduced by an Address, the subject of which has been left to the selection of the president for the time being. The perplexing duty of choosing a subject has not, however, fallen to me. Professor Sylvester, the president of Section A at the Exeter meeting, gave us a noble vindication of pure mathematics by laying bare, as it were, the very working of the mathematical mind, and setting before us, not the array of symbols and brackets which form the armoury of the mathematician, or the dry results which are only the monuments of his conquests, but the mathematician himself, with all his human faculties directed by his professional sagacity to the pursuit, apprehension, and exhibition of that ideal harmony which he feels to

be the root of all knowledge, the fountain of all pleasure, and the condition of all action. The mathematician has, above all things, an eye for symmetry; and Professor Sylvester has not only recognised the symmetry formed by the combination of his own subject with those of the former presidents, but has pointed out the duties of his successor in the following characteristic note:—

“Mr. Spottiswoode favoured the Section, in his opening address, with a combined history of the progress of mathematics and physics; Dr. Tyndall’s address was virtually on the limits of physical philosophy; the one here in print,” says Professor Sylvester, “is an attempted faint adumbration of the nature of mathematical science in the abstract. What is wanting (like a fourth sphere resting on three others in contact) to build up the ideal pyramid is a discourse on the relation of the two branches (mathematics and physics) to, and their action and reaction upon, one another—a magnificent theme, with which it is to be hoped that some future president of Section A will crown the edifice, and make the tetralogy (symbolisable by $A+A'$, A , A' , AA') complete.” [中文](#)

The theme thus distinctly laid down for his successor by our late President is indeed a magnificent one, far too magnificent for any efforts of mine to realise. I have endeavoured to follow Mr. Spottiswoode, as with far-reaching vision he distinguishes the systems of science into which phenomena, our knowledge of which is still in the nebulous stage, are growing. I have been carried by the penetrating insight and forcible expression of Dr. Tyndall into that sanctuary of minuteness and of power where molecules obey the laws of their existence, clash together in fierce collision, or grapple in yet more fierce embrace, building up in secret the forms of visible things. I have been guided by Professor Sylvester towards those serene heights

“Where never creeps a cloud, or moves a wind,

Nor ever falls the least white star of snow,
Nor ever lowest roll of thunder moans,
Nor sound of human sorrow mounts, to mar
Their sacred everlasting calm.”

But who will lead me into that still more hidden and dimmer region where Thought weds Fact; where the mental operation of the mathematician and the physical action of the molecules are seen in their true relation? Does not the way to it pass through the very den of the metaphysician, strewn with the remains of former explorers, and abhorred by every man of science? It would indeed be a foolhardy adventure for me to take up the valuable time of the section by leading you into those speculations which require, as we know, thousands of years even to shape themselves intelligibly. 中文

But we are met as cultivators of mathematics and physics. In our daily work we are led up to questions the same in kind with those of metaphysics; and we approach them, not trusting to the native penetrating power of our own minds, but trained by a long-continued adjustment of our modes of thought to the facts of external nature. As mathematicians, we perform certain mental operations on the symbols of number or of quantity, and, by proceeding step by step from more simple to more complex operations, we are enabled to express the same thing in many different forms. The equivalence of these different forms, though a necessary consequence of self-evident axioms, is not always, to our minds, self-evident; but the mathematician, who, by long practice, has acquired a familiarity with many of these forms, and has become expert in the processes which lead from one to another, can often transform a perplexing expression into another which explains its meaning in more intelligible language. 中文

As students of physics, we observe phenomena under varied circumstances, and endeavour to deduce the laws of their relations. Every natural phenomenon is, to our minds, the result of an infinitely

complex system of conditions. What we set ourselves to do is to unravel these conditions, and by viewing the phenomenon in a way which is in itself partial and imperfect, to piece out its features one by one, beginning with that which strikes us first, and thus gradually learning how to look at the whole phenomenon so as to obtain a continually greater degree of clearness and distinctness. In this process, the feature which presents itself most forcibly to the untrained inquirer may not be that which is considered most fundamental by the experienced man of science; for the success of any physical investigation depends on the judicious selection of what is to be observed as of primary importance, combined with a voluntary abstraction of the mind from those features which, however attractive they appear, we are not yet sufficiently advanced in science to investigate with profit. 中文

Intellectual processes of this kind have been going on since the first formation of language, and are going on still. No doubt the feature which strikes us first and most forcibly in any phenomenon, is the pleasure or the pain which accompanies it, and the agreeable or disagreeable results which follow after it. A theory of nature from this point of view is embodied in many of our words and phrases, and is by no means extinct even in our deliberate opinions. It was a great step in science when men became convinced that, in order to understand the nature of things, they must begin by asking, not whether a thing is good or bad, noxious or beneficial, but of what kind is it? and how much is there of it? Quality and quantity were then first recognised as the primary features to be observed in scientific inquiry. As science has been developed, the domain of quantity has everywhere encroached on that of quality, till the process of scientific inquiry seems to have become simply the measurement and registration of quantities, combined with a mathematical discussion of the numbers thus obtained. It is this scientific method of directing our attention to those features of phenomena which may be regarded as

quantities which brings physical research under the influence of mathematical reasoning. In the work of the section we shall have abundant examples of the successful application of this method to the most recent conquests of science; but I wish at present to direct your attention to some of the reciprocal effects of the progress of science on those elementary conceptions which are sometimes thought to be beyond the reach of change. 中文

If the skill of the mathematician has enabled the experimentalist to see that the quantities which he has measured are connected by necessary relations, the discoveries of physics have revealed to the mathematician new forms of quantities which he could never have imagined for himself. Of the methods by which the mathematician may make his labours most useful to the student of nature, that which I think is at present most important is the systematic classification of quantities. The quantities which we study in mathematics and physics may be classified in two different ways. The student who wishes to master any particular science must make himself familiar with the various kinds of quantities which belong to that science. When he understands all the relations between these quantities, he regards them as forming a connected system, and he classes the whole system of quantities together as belonging to that particular science. This classification is the most natural from a physical point of view, and it is generally the first in order of time. But when the student has become acquainted with several different sciences, he finds that the mathematical processes and trains of reasoning in one science resemble those in another so much that his knowledge of the one science may be made a most useful help in the study of the other. When he examines into the reason of this, he finds that in the two sciences he has been dealing with systems of quantities, in which the mathematical forms of the relations of the quantities are the same in both systems, though the physical nature of the quantities may be utterly different. He is thus led to recognise a classification of

quantities on a new principle, according to which the physical nature of the quantity is subordinated to its mathematical form. This is the point of view which is characteristic of the mathematician; but it stands second to the physical aspect in order of time, because the human mind, in order to conceive of different kinds of quantities, must have them presented to it by nature. I do not here refer to the fact that all quantities, as such, are subject to the rules of arithmetic and algebra, and are therefore capable of being submitted to those dry calculations which represent, to so many minds, their only idea of mathematics. The human mind is seldom satisfied, and is certainly never exercising its highest functions, when it is doing the work of a calculating machine. What the man of science, whether he be a mathematician or a physical inquirer, aims at is, to acquire and develop clear ideas of the things he deals with. For this purpose he is willing to enter on long calculations, and to be for a season a calculating machine, if he can only at last make his ideas clearer. But if he finds that clear ideas are not to be obtained by means of processes, the steps of which he is sure to forget before he has reached the conclusion, it is much better that he should turn to another method, and try to understand the subject by means of well-chosen illustrations derived from subjects with which he is more familiar. We all know how much more popular the illustrative method of exposition is found, than that in which bare processes of reasoning and calculation form the principal subject of discourse. Now a truly scientific illustration is a method to enable the mind to grasp some conception or law in one branch of science, by placing before it a conception or a law in a different branch of science, and directing the mind to lay hold of that mathematical form which is common to the corresponding ideas in the two sciences, leaving out of account for the present the difference between the physical nature of the real phenomena. The correctness of such an illustration depends on whether the two systems of ideas which are compared together are really analogous in form, or whether, in other words, the

corresponding physical quantities really belong to the same mathematical class. When this condition is fulfilled, the illustration is not only convenient for teaching science in a pleasant and easy manner, but the recognition of the mathematical analogy between the two systems of ideas leads to a knowledge of both, more profound than could be obtained by studying each system separately. 中文

There are men who, when any relation or law, however complex, is put before them in a symbolical form, can grasp its full meaning as a relation among abstract quantities. Such men sometimes treat with indifference the further statement that quantities actually exist in nature which fulfil this relation. The mental image of the concrete reality seems rather to disturb than to assist their contemplations. But the great majority of mankind are utterly unable, without long training, to retain in their minds the unembodied symbols of the pure mathematician; so that if science is ever to become popular and yet remain scientific, it must be by a profound study and a copious application of those principles of truly scientific illustration which, as we have seen, depend on the mathematical classification of quantities. There are, as I have said, some minds which can go on contemplating with satisfaction pure quantities presented to the eye by symbols, and to the mind in a form which none but mathematicians can conceive. There are others who feel more enjoyment in following geometrical forms, which they draw on paper, or build up in the empty space before them. Others, again, are not content unless they can project their whole physical energies into the scene which they conjure up. They learn at what a rate the planets rush through space, and they experience a delightful feeling of exhilaration. They calculate the forces with which the heavenly bodies pull at one another, and they feel their own muscles straining with the effort. 中文

To such men impetus, energy, mass, are not mere abstract expressions of the results of scientific inquiry. They are words of power which stir

their souls like the memories of childhood. For the sake of persons of these different types, scientific truths should be presented in different forms, and should be regarded as equally scientific, whether it appears in the robust form and the vivid colouring of a physical illustration, or in the tenuity and paleness of a symbolical expression. Time would fail me if I were to attempt to illustrate by examples the scientific value of the classification of quantities. I shall only mention the name of that important class of magnitudes having direction in space which Hamilton has called Vectors, and which form the subject-matter of the Calculus of Quaternions—a branch of mathematics which, when it shall have been thoroughly understood by men of the illustrative type, and clothed by them with physical imagery, will become, perhaps under some new name, a most powerful method of communicating truly scientific knowledge to persons apparently devoid of the calculating spirit. The mutual action and reaction between the different departments of human thought is so interesting to the student of scientific progress, that, at the risk of still further encroaching on the valuable time of the Section, I shall say a few words on a branch of science which not very long ago would have been considered rather a branch of metaphysics: I mean the atomic theory, or, as it is now called, the molecular theory of the constitution of bodies. Not many years ago, if we had been asked in what regions of physical science the advance of discovery was least apparent, we should have pointed to the hopelessly distant fixed stars on the one hand, and to the inscrutable delicacy of the texture of material bodies on the other. Indeed, if we are to regard Comte as in any degree representing the scientific opinion of his time, the research into what takes place beyond our own solar system seemed then to be exceedingly unpromising, if not altogether illusory. The opinion that the bodies which we see and handle, which we can set in motion or leave at rest, which we can break in pieces and destroy, are composed of smaller bodies which we cannot see or handle, which are always in motion, and which can neither be stopped nor broken in pieces, nor in

any way destroyed or deprived of the least of their properties, was known by the name of the Atomic Theory. It was associated with the names of Democritus and Lucretius, and was commonly supposed to admit the existence only of atoms and void, to the exclusion of any other basis of things from the universe. [中文](#)

In many physical reasonings and mathematical calculations we are accustomed to argue as if such substances as air, water, or metal, which appear to our senses uniform and continuous, were strictly and mathematically uniform and continuous. We know that we can divide a pint of water into many millions of portions, each of which is as fully endowed with all the properties of water as the whole pint was, and it seems only natural to conclude that we might go on subdividing the water for ever, just as we can never come to a limit in subdividing the space in which it is contained. We have heard how Faraday divided a grain of gold into an inconceivable number of separate particles, and we may see Dr. Tyndall produce from a mere suspicion of nitrite of butyle an immense cloud, the minute visible portion of which is still cloud, and therefore must contain many molecules of nitrite of butyle. But evidence from different and independent sources is now crowding in upon us which compels us to admit that if we could push the process of subdivision still further we should come to a limit, because each portion would then contain only one molecule, an individual body, one and indivisible, unalterable by any power in nature. Even in our ordinary experiments on very finely divided matter we find that the substance is beginning to lose the properties which it exhibits when in a large mass, and that effects depending on the individual action of molecules are beginning to become prominent. The study of these phenomena is at present the path which leads to the development of molecular science. That superficial tension of liquids which is called capillary attraction is one of these phenomena. Another important class of phenomena are those which are due to that motion of agitation by which the molecules of a liquid

or gas are continually working their way from one place to another, and continually changing their course, like people hustled in a crowd. On this depends the rate of diffusion of gases and liquids through each other, to the study of which, as one of the keys of molecular science, that unwearied inquirer into nature's secrets, the late Prof. Graham, devoted such arduous labour. 中文

The rate of electrolytic conduction is, according to Wiedemann's theory, influenced by the same cause; and the conduction of heat in fluids depends probably on the same kind of action. In the case of gases, a molecular theory has been developed by Clausius and others, capable of mathematical treatment, and subjected to experimental investigation; and by this theory nearly every known mechanical property of gases has been explained on dynamical principles, so that the properties of individual gaseous molecules are in the fair way to become objects of scientific research. Now Sir William Thomson has shown by several independent lines of argument, drawn from phenomena so different in themselves as the electrification of metals by contact, the tension of soap-bubbles, and the friction of air, that in ordinary solids and liquids the average distance between contiguous molecules is less than the hundred-millionth, and greater than the two-thousand-millionth of a centimetre. This of course is an exceedingly rough estimate, for it is derived from measurements, some of which are still confessedly very rough; but if, at the present time, we can form even a rough plan for arriving at a result of this kind, we may hope that as our means of experimental inquiry become more accurate and more varied, our conception of a molecule will become more definite, so that we may be able at no distant period to estimate its weight. A theory which Sir W. Thomson has founded on Helmholtz's splendid hydrodynamical theorems, seeks for the properties of molecules in the ring-vortices of a uniform, frictionless, incompressible fluid. Such whirling rings may be seen when an experienced smoker sends out a dexterous puff of smoke into the still

air, but a more evanescent phenomenon it is difficult to conceive. This evanescence is owing to the viscosity of the air; but Helmholtz has shown that in a perfect fluid such a whirling ring, if once generated, would go on whirling for ever, would always consist of the very same portion of the fluid which was first set whirling, and could never be cut in two by any natural cause. The generation of a ring-vortex is of course equally beyond the power of natural causes, but once generated, it has the properties of individuality, permanence in quantity, and indestructibility. It is also the recipient of impulse and of energy, which is all we can affirm of matter; and these ring-vortices are capable of such varied connections, and knotted self-involutions, that the properties of differently knotted vortices must be as different as those of different kinds of molecules can be. [中文](#)

If a theory of this kind should be found, after conquering the enormous mathematical difficulties of the subject, to represent in any degree the actual properties of molecules, it will stand in a very different scientific position from those theories of molecular action which are formed by investing the molecule with an arbitrary system of central forces invented expressly to account for the observed phenomena. In the vortex theory we have nothing arbitrary, no central forces or occult properties of any other kind. We have nothing but matter and motion, and when the vortex is once started its properties are all determined from the original impetus, and no further assumptions are possible. Even in the present undeveloped state of the theory, the contemplation of the individuality and indestructibility of a ring vortex in a perfect fluid cannot fail to disturb the commonly received opinion that a molecule, in order to be permanent, must be a very hard body. In fact one of the first conditions which a molecule must fulfil is, apparently, inconsistent with its being a single hard body. We know from those spectroscopic researches which have thrown so much light on different branches of science, that a molecule can be set into a state of internal vibration, in

which it gives off to the surrounding medium light of definite refrangibility—light, that is, of definite wave-length and definite period of vibration. The fact that all the molecules, say of hydrogen, which we can procure for our experiments, when agitated by heat or by the passage of an electric spark, vibrate precisely in the same periodic time, or, to speak more accurately, that their vibrations are composed of a system of simple vibrations having always the same periods, is a very remarkable fact. I must leave it to others to describe the progress of that splendid series of spectroscopic discoveries by which the chemistry of the heavenly bodies has been brought within the range of human inquiry. I wish rather to direct your attention to the fact that not only has every molecule of terrestrial hydrogen the same system of periods of free vibration, but that the spectroscope examination of the light of the sun and stars shows that in regions the distance of which we can only feebly imagine there are molecules vibrating in as exact unison with the molecules of terrestrial hydrogen as two tuning forks tuned to correct pitch, or two watches regulated to solar time. Now this absolute equality in the magnitude of quantities, occurring in all parts of the universe, is worth our consideration. The dimensions of individual natural bodies are either quite indeterminate, as in the case of planets, stones, trees, &c., or they vary within moderate limit, as in the case of seeds, eggs, &c.; but, even in these cases, small quantitative differences are met with which do not interfere with the essential properties of the body. Even crystals, which are so definite in geometrical form, are variable with respect to their absolute dimensions. Among the works of man we sometimes find a certain degree of uniformity. There is a uniformity among the different bullets which are cast in the same mould, and the different copies of a book printed from the same type. If we examine the coins, or the weights and measures, of a civilised country, we find a uniformity, which is produced by careful adjustment to standards made and provided by the State. The degree of uniformity of these national standards is a measure of that spirit of justice in the nation

which has enacted laws to regulate them and appointed officers to test them. This subject is one in which we, as a scientific body, take a warm interest, and you are all aware of the vast amount of scientific work which has been expended, and profitably expended, in providing weights and measures for commercial and scientific purposes. The earth has been measured as a basis for a permanent standard of length, and every property of metals has been investigated to guard against any alteration of the material standards when made. To weigh or measure anything with modern accuracy, requires a course of experiment and calculation in which almost every branch of physics and mathematics is brought into requisition. 中文

Yet, after all, the dimensions of our earth and its time of rotation, though, relatively to our present means of comparison, very permanent, are not so by any physical necessity. The earth might contract by cooling, or it might be enlarged by a layer of meteorites falling on it, or its rate of revolution might slowly slacken, and yet it would continue to be as much a planet as before. But a molecule, say of hydrogen, if either its mass or its time of vibration were to be altered in the least, would no longer be a molecule of hydrogen. If, then, we wish to obtain standards of length, time, and mass which shall be absolutely permanent, we must seek them not in the dimensions, or the motion, or the mass of our planet, but in the wavelength, the period of vibration, and the absolute mass of these imperishable and unalterable and perfectly similar molecules. When we find that here, and in the starry heavens, there are innumerable multitudes of little bodies of exactly the same mass, so many, and no more, to the grain, and vibrating in exactly the same time, so many times, and no more, in a second, and when we reflect that no power in nature can now alter in the least either the mass or the period of any one of them, we seem to have advanced along the path of natural knowledge to one of those points at which we must accept the guidance of that faith by which we understand that “that which is

seen was not made of things which do appear.” One of the most remarkable results of the progress of molecular science is the light it has thrown on the nature of irreversible processes,—processes, that is, which always tend towards, and never away from, a certain limiting state. Thus if two gases be put into the same vessel they become mixed, and the mixture tends continually to become more uniform. If two unequally heated portions of the same gas are put into the vessel, something of the kind takes place, and the whole tends to become of the same temperature. If two unequally heated solid bodies be placed in contact, a continual approximation of both to an intermediate temperature takes place. In the case of the two gases, a separation may be effected by chemical means; but in the other two cases the former state of things cannot be restored by any natural process. In the case of the conduction or diffusion of heat the process is not only irreversible, but it involves the irreversible diminution of that part of the whole stock of thermal energy which is capable of being converted into mechanical work. This is Thomson’s theory of the irreversible dissipation of energy, and it is equivalent to the doctrine of Clausius concerning the growth of what he calls Entropy. The irreversible character of this process is strikingly embodied in Fourier’s theory of the conduction of heat, where the formulae themselves indicate a possible solution of all positive values of the time which continually tends to a uniform diffusion of heat. But if we attempt to ascend the stream of time by giving to its symbol continually diminishing values, we are led up to a state of things in which the formula has what is called a critical value; and if we inquire into the state of things the instant before, we find that the formula becomes absurd. We thus arrive at the conception of a state of things which cannot be conceived as the physical result of a previous state of things, and we find that this critical condition actually existed at an epoch not in the utmost depths of a past eternity, but separated from the present time by a finite interval. This idea of a beginning is one which the physical researches of recent times have brought home to us, more than any

observer of the course of scientific thought in former times would have had reason to expect. But the mind of man is not like Fourier's heated body, continually settling down into an ultimate state of quiet uniformity, the character of which we can already predict; it is rather like a tree shooting out branches which adapt themselves to the new aspects of the sky towards which they climb, and roots which contort themselves among the strange strata of the earth into which they delve. To us who breathe only the spirit of our own age, and know only the characteristics of contemporary thought, it is as impossible to predict the general tone of the science of the future as it is to anticipate the particular discoveries which it will make. Physical research is continually revealing to us new features of natural processes, and we are thus compelled to search for new forms of thought appropriate to these features. Hence the importance of a careful study of those relations between mathematics and physics which determine the conditions under which the ideas derived from one department of physics may be safely used in forming ideas to be employed in a new department. The figure of speech or of thought by which we transfer the language and ideas of a familiar science to one with which we are less acquainted may be called scientific metaphor. Thus the words velocity, momentum, force, &c., have acquired certain precise meanings in elementary dynamics. They are also employed in the dynamics of a connected system in a sense which, though perfectly analogous to the elementary sense, is wider and more general. These generalised forms of elementary ideas may be called metaphorical terms in the sense in which every abstract term is metaphorical. The characteristic of a truly scientific system of metaphors is that each term in its metaphorical use retains all the formal relations to the other terms of the system which it had in its original use. The method is then truly scientific, that is, not only a legitimate product of science, but capable of generating science in its turn. There are certain electrical phenomena, again, which are connected together by relations of the same form as those which connect dynamical

phenomena. To apply to these the phrases of dynamics with proper distinctions and provisional reservations is an example of a metaphor of a bolder kind; but it is a legitimate metaphor if it conveys a true idea of the electrical relations to those who have been already trained in dynamics. Suppose, then, that we have successfully introduced certain ideas belonging to an elementary science by applying them metaphorically to some new class of phenomena. It becomes an important philosophical question to determine in what degree the applicability of the old ideas to the new subject may be taken as evidence that the new phenomena are physically similar to the old. The best instances for the determination of this question are those in which two different explanations have been given of the same thing. The most celebrated case of this kind is that of the corpuscular and the undulatory theories of light. Up to a certain point the phenomena of light are equally well explained by both; beyond this point one of them fails. To understand the true relation of these theories in that part of the field where they seem equally applicable we must look at them in the light which Hamilton has thrown upon them by his discovery that to every brachystochrone problem there corresponds a problem of free motion, involving different velocities and times, but resulting in the same geometrical path. Professor Tait has written a very interesting paper on this subject. According to a theory of electricity which is making great progress in Germany two electrical particles act on one another directly at a distance, but with a force which, according to Weber, depends on their relative velocity, and according to a theory hinted at by Gauss, and developed by Riemann, Lorenz, and Neumann, acts not instantaneously, but after a time depending on the distance. The power with which this theory, in the hands of these eminent men, explains every kind of electrical phenomena must be studied in order to be appreciated. Another theory of electricity which I prefer denies action at a distance and attributes electric action to tensions and pressures in an all-pervading medium, these stresses being the same in kind with those familiar to

engineers, and the medium being identical with that in which light is supposed to be propagated. Both these theories are found to explain not only the phenomena by the aid of which they were originally constructed, but other phenomena which were not thought of, or perhaps not known at the time, and both have independently arrived at the same numerical result which gives the absolute velocity of light in terms of electrical quantities. That theories, apparently so fundamentally opposed, should have so large a field of truth common to both is a fact the philosophical importance of which we cannot fully appreciate till we have reached a scientific altitude from which the true relation between hypotheses so different can be seen. 中

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I shall only make one more remark on the relation between mathematics and physics. In themselves, one is an operation of the mind, the other is a dance of molecules. The molecules have laws of their own, some of which we select as most intelligible to us and most amenable to our calculation. We form a theory from these partial data, and we ascribe any deviation of the actual phenomena from this theory to disturbing causes. At the same time, we confess that what we call disturbing causes are simply those parts of the true circumstances which we do not know or have neglected, and we endeavour in future to take account of them. We thus acknowledge that the so-called disturbance is a mere figment of the mind, not a fact of nature, and that in natural action there is no disturbance. But this is not the only way in which the harmony of the material with the mental operation may be disturbed. The mind of the mathematician is subject to many disturbing causes, such as fatigue, loss of memory, and hasty conclusions; and it is found that from these and other causes mathematicians make mistakes. I am not prepared to deny that, to some mind of a higher order than ours, each of these errors might be traced to the regular operation of the laws of actual thinking; in fact we ourselves often do detect, not only errors of calculation, but the

causes of these errors. This, however, by no means alters our conviction that they are errors, and that one process of thought is right and another process wrong. One of the most profound mathematicians and thinkers of our time, the late George Boole, when reflecting on the precise and almost mathematical character of the laws of right thinking as compared with the exceedingly perplexing, though perhaps equally determinate, laws of actual and fallible thinking, was led to another of those points of view from which science seems to look out into a region beyond her own domain. “We must admit,” he says, “that there exist laws” (of thought) “which even the rigour of their mathematical forms does not preserve from violation. We must ascribe to them an authority, the essence of which does not consist in power, a supremacy which the analogy of the inviolable order of the natural world in no way assists us to comprehend.” [中文](#)

(2, 419-422; 1870)

数学和物理科学

麦克斯韦

詹姆斯·克拉克·麦克斯韦可以算是19世纪后半叶最敏锐的物理学家了，他是英国科学促进会1870年会议的物理分会主席。他认为自己的主席演说受到了数学家凯莱在前一年发表的演说的启发。这篇演讲稿论述了在解释物理现象时分子所起到的作用。 [英文](#)

主席发表了如下演讲：

在最近几次英国科学促进会的会议上，有一次演讲指出了数学和物理分会中各种重要的事务，因而这一演讲主题被纳入了现任主席的选择。不过，选择主题这一艰巨的任务并没有落在我身上。埃克塞特会议中担任第一分会主席的西尔维斯特教授为我们带来了纯数学的庄严拥护，通过直截了当地提出数学头脑所从事的真正工作，他呈现给我们的不仅仅是从数学家的武器库中取出的符号和括号的堆砌品，也不仅仅是只有数学家自得其乐的干巴巴的结果，而是一位数学家本身，在职业睿智的指引下，将全部的个人才华都用于追求、理解和展示在他看来是一切知识之本、快乐之源与行为之因的理想的和谐一致。最重要的是，数学家有着调和的眼光；西尔维斯特教授不仅考虑到将他本人的主题与此前各位主席所演讲的主题相结合，还在下面这段典型的文字中指出了后继者的职责：

“斯波蒂斯伍德先生在他的公开演讲中称这一分会为数学与物理发展历史的结合；廷德尔博士的演讲将其本质界定为物理哲学；在这份出版物中，”西尔维斯特教授讲到，“它是一种尝试性的、对于数学科学抽象本质的模糊概括。建立这座理想的金字塔还需要的（如同置于三个彼此接触的球之上的第四个球）是一场涉及两大分支学科（数学和物理）的关系及其相互作用与反作用的讨论——这是一个宏大的主题，期望第一

分会未来的某位主席能够为这座大厦剪彩，并完成这出四部曲（可以符号化地表示为 $A + A'$ ， A ， A' ， AA' ）。” 英文

我们的前任主席为其继任者清晰规划出的这一主题的确是宏伟的，以至于尽我所有的努力都无法将其实现。我曾努力追随斯波蒂斯伍德先生，他以深远的见地将科学系统归类成各种不断增长的现象，而我们对于这些现象的认识还处于蒙昧状态。我也曾被廷德尔博士那敏锐的洞察力和有力的陈述带入那个力量与精微的圣殿，在那里，分子遵循着自身存在的定律，猛烈地撞在一起，或者在更为热烈的拥抱中纠缠，就这样悄然形成了事物的可见形式。我曾被西尔维斯特教授引领向那些宁静的峰巅

“那里从没有云的踪迹，或风的迹象，
从不曾有些微雪花的斑痕，
从不曾有丝毫雷电的呼啸，
或是人类的悲怨之声，能够破坏，
他们那庄严持久的宁静。”

然而，谁能引领我进入那更为隐蔽与晦暗的思想与事实交汇的地带，数学家的头脑运算与分子间的物理作用呈现出其真实关联的所在在哪里呢？难道这条路不会经过那遍布着早期探索者的遗迹并被每一位科研工作者所痛恨的形而上学家的巢穴吗？对于我来说，占用整个分会的宝贵时间将各位引入那些就我们所知需要用几千年时间才能建立成型的思考中，实在是一种莽撞的冒险。 英文

然而，我们是别人眼中数学和物理的耕耘者。在日常工作中，我们向形而上学家遇到的同类型的问题进军；我们着手处理那些问题，但并不完全寄希望于我们与生俱来的洞察力，而是通过长期持续地调整自身思维模式使之符合客观自然现象来训练自己。作为数学家，我们对数字与数量符号进行特定的大脑运算，并且通过从易到难的运算一步一步地推导，我们可以用多种不同形式表达同一事物。尽管这些形式之间的等价性是不证自明的公理的必然推论，但是对我们的头脑来说却并不总是不言而喻的；而数学家们，经过长期的实践已经对其中诸多形式颇为熟悉，并且已经成为将一种形式转变为另一种形式这一过程的专家，他们

经常能够将一种复杂的表达形式转变为另外一种能以更容易被理解的语言解释其含义的形式。 [英文](#)

作为物理研究者，我们在各种条件下观察现象，并致力于归纳出表达这些现象之间关联的定律。对我们的头脑来说，每一种自然现象都是一个无限复杂的条件体系的结果。我们努力做的就是将这些条件分解，用本身就是局部的、不完全的方式来观察现象，然后从我们最初遇到的那些开始，将现象的特征一个接一个地拼凑起来，并由此逐渐了解到该如何看待整个现象才能使明确度与清晰度不断增加。在这一过程中，那些在未经训练的研究者看来表现得最为强烈的特征，可能在有经验的科学工作者看来并不是最根本的性质；因为任何物理研究的成功都取决于在所观察到的一切中对于首要因素的明智选择，还要结合对那些尽管看来很诱人却还未能充分有益于科学研究的想法的自觉提炼。 [英文](#)

这种理性过程自从语言形成以来就一直在进行着，并且还要进行下去。无疑，在任何现象中，最先刺激我们并表现得最为强烈的特征，就是伴随该现象而来的喜悦或烦恼，以及接踵而至的一致或不一致的结果。一种基于此看法的自然理论体现在很多词汇和短语中，而且即使在经过深思熟虑的观点中也不会消逝。当人们最终深信，为了理解事物的本质，他们一开始必须询问的不是该事物是好还是坏、是有害的还是有益的，而是它属于哪一类别、具体有多少时，科学便迈出了伟大的一步。自此，定性和定量第一次被认为是科学研究中要观察的首要特征。科学一旦建立起来，定量的疆域就会从各个角落侵占定性的疆域，直到科学研究的过程逐渐变为只是数量的测量与记录再加上对由此获得的数字的数学讨论。正是这种将我们的注意力引向自然现象中那些可以被视为量的特征的科学方法，把我们带入了数学推理影响下的物理研究中。在本分会所涉及的研究工作中，我们有丰富的实例可以说明这种方法在最近的科学成就中的成功应用；但是现在，我希望可以将各位的注意力引向科学发展对那些有时被认为是亘古不变的基本概念的相反的影响。

[英文](#)

如果说数学家的技艺使实验家看到了他已测量的量之间有着必然的联系，物理的发现则已向数学家揭示出他们自己绝对无法想象出来的量的新形式。在数学家作为自然界的研究者付出辛劳时所用到的最有益的

方法中，我认为当前最重要的方法就是量的系统分类。我们在数学和物理中所研究的量可以用两种不同的方式分类。想要掌握任何一门特定科学的学生必须使自己熟悉该科学的各种量。一旦他理解了这些量之间的全部关联，就会认为它们形成了一个联结起来的体系，并把整个量的体系归在一起作为属于该特定科学的类。从物理的观点来看这种分类法是最自然的，并且在时间上一般也是最先出现的。但是当这名学生逐渐通晓了若干个不同学科时，他会发现在一门科学中的数学过程和推理训练与另外一门中的十分相似，以至于在一门科学中的知识对于学习另外一门科学极有帮助。在分析其中的道理时，他会发现，在需要处理包含各自量的系统的两门科学中，尽管各自的量的物理本质可能是完全不同的，但两个系统中量之间关系的数学形式是一样的。由此，他认识到基于一种新原则的量的分类法，根据这一原则，量的物理本质服从于其数学形式。这是带有数学家特征的观点；不过在时间顺序上它位于物理观点之后，因为，为了使人类的头脑能够想象出不同种类的量，首先它们本身就必须是确实存在的。这里我并没有提及这样的事实，即所有的量本身都必须服从代数和几何规则，并因此服从于很多人认为的是代表其唯一数学观念的那些干巴巴的计算。人类的头脑在从事计算机器的工作时，很少会得到满足，当然也不会用到其最高级的功能。无论是数学家还是物理学者，科学工作者所希求的，是获得和发展有关他所研究的事物的清晰观念。为了这个目的，他甘愿投身于漫长的计算，并暂时充当一台计算机器，只要最终能使自己的观念变得清晰一些。不过，要是他发现通过某种过程（在得到计算结果之前就必然已把前面的步骤忘光的过程）不可能获得清晰的观念，那么他最好还是换一种方法，并通过在他比较熟悉的学科衍生出的种种解释中仔细挑选出的解释，来理解这个学科。我们都知道，直观的解释方法比从讨论主题出发进行干巴巴的推导和计算的过程受欢迎得多。那么，一个真正的科学解释是使头脑能够掌握某一科学分支中的一些概念和定律的方法，这是通过以下方式实现的：在头脑中呈现出另一科学分支中的一个概念或一条定律，并指引头脑去把握两个科学分支的对应观念中所共有的数学形式，而不去考虑那些真实现象的物理本质之间的不同。这样一种解释的正确性取决于两个放在一起比较的观念体系是否真的在形式上相似，或者换句话说，相应的物理量是否真的属于同一数学类。一旦满足了这一条件，不仅这种解释便于以轻松愉快的方式进行科学教学，而且对两个观念体系之间数学

上的相似性的认识还会促进这两个系统的知识的发展，这就比我们单独研究任何一门科学所能获得的知识更加深刻。 [英文](#)

任何一种无论多么复杂的关系或定律以符号形式呈现在人们面前时，总有人能够把握到它作为抽象的量之间关系的全部含义。有时，这些人对那些满足这一关系的自然界真实存在的量的进一步阐述毫不关心。具体现实在头脑中的印象似乎对他们思考的干扰多于帮助。但是，若非经过长期训练，绝大多数人绝对没法在其头脑中记住纯数学家的抽象符号。因此，如果科学想要广受欢迎同时保持科学性，它就必须经历深入的研究，以及能用真正的科学进行解释的原理的大量应用。而这，如同我们已经看到的，有赖于量的数学分类。正如我在前面提到的，有些头脑满足于利用那些纯粹的量进行思考，这些量以符号的形式呈现在他们眼前，并以某种除了数学家之外无人可以理解的形式展示于他们的头脑中。而另外一些人则以研究几何形式为乐，他们将几何形式描绘在纸上，或搭建在面前的空间中。还有一些人，只满足于将其全部精力投入到他们在头脑中幻想出的景象。他们研究行星掠过太空时的速度，从中体会喜悦的满足感。他们计算天体彼此之间的牵引力，并感觉自己的肌肉在这种作用下的变形。 [英文](#)

对这样的人来说，冲量、能量和质量不仅仅是科学研究结果的抽象表达，它们还是如同童年记忆一样可以触动这些人灵魂的有力文字。因为上述不同类型的人，所以科学真理应该以不同的形式表达，而且无论它出现在充实的表格和生动多彩的物理图解中，还是单调苍白的方程中，都应该被视为具有同等的科学性。时间不允许我在这里通过举例来说明量的分类的科学意义。我只能稍微说说被哈密顿称为矢量的一类具有空间方向的重要量，这正是四元数微积分的主题。四元数微积分是这样一个数学分支：当它完全被善于作举例说明的人所理解并被他们赋予丰富的物理想象的时候，它（也可能起了新名字）就会成为向那些看似缺乏计算头脑的人们传达真正科学知识的最有力的方法。人类思维的各个不同部分之间的相互作用和反作用对科学过程的研究者来说是如此有趣，以至于即使冒着继续侵占整个分会宝贵时间的风险，我也要说明一个在不久之前还被看作是形而上学的科学分支，即，关于物体构成的原子理论或者说分子理论（现在是这样叫的）。几年前，如果有人问物

理学中哪个领域进展最缓慢，我们会一手指向令人绝望的远地星体，另一手指向神秘的物质结构。的确，如果我们认为在任何情况下孔德都可以代表他所在时代的科学观点，那么对于发生在太阳系之外的事物的研究即使不是幻想，也只是毫无希望的事情。我们可以看到和触碰的、可以发动和制动的、可以打碎和毁灭的物体都是由我们看不到也触碰不到、一直处于运动状态并且不能被我们阻止、打碎、毁灭或剥夺其任何性质的更小的物体组成的，这种观点就是所谓的原子理论。这一理论与德谟克利特和卢克莱修这两个名字相联系，并且一般假定只承认原子和空隙的存在，而排除宇宙中其他一切物质基础的存在。 [英文](#)

在很多物理推导和数学计算中，我们习惯地认为诸如空气、水或金属这些给我们均匀、连续的感觉的物质在数学上是严格均匀和连续的。我们知道，我们可以将一品脱水分成数百万份，每一份水都具有这一品脱水作为一个整体时所具有的所有性质，很自然地我们会得出这样的结论：我们可以无限细分这些水，就如同我们可以无限细分盛有这些水的空间一样。我们已经听说法拉第是如何将一粒金子分成不计其数的分离颗粒，而且我们可能会看到廷德尔博士用少量的丁基硝酸盐生成了一个巨大的云团，这个大云团的可见的微小部分仍是云团，因此一定包含很多丁基硝酸盐分子。然而，从各个独立的渠道所获得的证据正朝我们涌来，这迫使我们承认如果将细分过程继续推进，我们将会遇到一个极限，因为这时每一部分只包含一个分子，这是一种不能被任何自然界的力量分割或改变的独立个体。即使是在平时关于分得很细的物质的实验中，我们也会发现这些物质已经开始失去作为大块材料时所具有的一些性质，产生这一结果的原因是分子的个别作用开始变得显著。目前，研究这种现象是分子科学发展的一种途径。被称为毛细引力的液体表面张力就是这种现象中的一个。另一类重要的现象是那些由激发运动产生的现象，由于激发运动，液态或气态分子不断从一个地方运动到另一个地方，并且不断变化它们的航向，就如同人群中奔忙的人那样。这种运动决定了气体和液体相互扩散的速度，对此类现象的研究正是永不停歇地探寻自然之谜的分子科学的关键点之一，已故的格雷姆教授为此付出了非常艰辛的努力。 [英文](#)

根据维德曼的理论，电解导电速率也受到相同原因的影响；流体中

的热传导可能也取决于同类作用。气体分子理论已经由克劳修斯和其他研究者发展成熟，可以用数学方法处理，并且与实验研究结果相符。应用这个理论，气体的几乎所有已知的力学性质都可以用动力学原理解释，因此，单个气体分子的性质就理所当然地成了科学研究的目标。现在，威廉·汤姆孙爵士通过一些各自独立的现象，例如金属的接触带电、肥皂泡的张力和空气的摩擦力，从不同角度证明了在普通的固体和流体中近邻分子之间的平均距离在 $5 \times 10^{-10} \sim 1 \times 10^{-8}$ 厘米之间。当然这是一个非常粗略的估算，因为导出这个估算值的测量中包含着一些仍旧被公认为非常粗略的结果，但是如果到目前为止，可以建立一套能够获得这类结果的哪怕只是粗略的计划，我们可能就会希望随着实验研究手段的越来越精确和多样化，我们对单个分子的概念会越来越清晰，这样，在不远的将来，我们就能够估算它的质量。基于亥姆霍兹精妙的流体动力学定理，汤姆孙爵士建立了一个研究分子在均匀、无摩擦且不可压缩的液体环形漩涡中的性质的理论。当一个有经验的吸烟者向静止的空气中吐出一个烟圈时就能够看到这样的涡流环，但是这是一个非常短暂的现象，很难去想象。这种短暂性是空气的粘性造成的；但是，亥姆霍兹认为在完全流体中，这样的涡流环一旦产生就会永远涡旋下去，而且一直是由开始成为涡旋的那部分流体组成，决不会被任何自然力分成两半。当然，环形漩涡的产生也同样不是出于自然原因，但是一旦产生，它就具有个体特征、量的恒定和不可摧毁性。我们能够断言的仅仅是漩涡，也就是冲量和能量的接受者，可以认为是一种物质；这些环形漩涡具有如此多样的关系和自卷结，以至于不同的涡流结一定像不同的分子一样属于不同的类型。 [英文](#)

如果在解决了这个问题的大量数学疑难之后，可以找到一个这种类型的理论来表示分子的所有真实性质，那么这个理论将处于与那些在研究具有主观中心力系统（这个系统是为了解释宏观现象而臆造的）的分子时形成的分子相互作用理论非常不同的科学地位。在涡旋理论中，没有什么主观的，没有中心力或其他任何类型的超自然性质。只存在物质和运动，而且一旦涡旋产生，它的性质就完全取决于初始的动力，可以不用做任何进一步的假设。即使是在目前这种理论尚未发展成熟的情况下，关于完全流体中环形漩涡的个别性和不可毁灭性的思考也会扰乱人们的普遍观点：为了具有永久性，分子必须是非常坚硬的个体。事实

上，分子必须满足的一个首要条件似乎与它是一个单一坚硬个体这一观点是不一致的。我们从已经惠及多门科学分支的光谱研究可以知道，分子能够调节到内部振动状态，在这种状态下，分子向周围介质辐射具有确定折射率的光（即，该光具有确定的波长和确定的振动周期）。所有可以为我们的实验服务的分子，比如氢分子，当它们受热激发时或在电火花经过而引起激发时，都会精确地以相同的周期振动，或者更准确地说，它们的振动是由一个具有相同振动周期的简单振动系统组成的，事实的确如此。我不得不把一系列精彩的光谱学发现留给别人去描述，尽管正是这些精彩的发现将天体化学这一领域纳入了人类探索的范围。我宁愿将你们的注意力引到这样的事实中：不仅地球上每一个氢分子都有相同的自由振动周期系统，而且对太阳和行星发出的光的光谱检测结果表明，在那些与地球之间的距离大到无法想象的行星上，也有与地球上氢分子的振动完全一致的分子振动，就好像两个被调节到相同音调的音叉，或者两块校准到太阳时的表。那么这种发生在宇宙各个部分的量在量值上的绝对等价性就值得我们思考。自然个体的尺度不是非常不确定（比如，行星、石块、树木等），就是能够在适度的范围内变化（比如，种子、卵等）；但是即使在这些例子中所遇到的量值上微小的不同也不会影响物体的本质特征。即使是具有非常确定的几何形状的晶体，其绝对尺寸也是可变的。在人类的工作中我们时常会发现一定程度的一致性。比如，同一模子中铸造出的不同子弹具有一致性，同一版次印刷出的书籍的不同副本具有一致性。如果我们观察一个文明国家的货币和度量衡，也会发现一致性，一种产生于按国家规定的标准仔细调节的一致性。这些国家标准的一致程度是对这个制定了法律来规范各种标准并且委派了官员来检测各种标准的国家的公平意识程度的衡量。作为科学个体来说，这个主题是我们很感兴趣的问题，并且大家都意识到大量科学工作已经投入并且有利地投入到为商业或科学目的提供度量衡之中。地球作为长度的永久基准已经得到了测量，同时金属的每一个性质都已经得到了研究，目的是为了在制造过程中避免材料标准的任何改变。以现在的精度去称量或测量任何东西，都需要经过一个实验和计算的过程，这个过程几乎会用到物理和数学的所有分支。 [英文](#)

虽然地球的尺寸及其自转的时间相对于我们现有的比较方法来说是永恒不变的，但毕竟不是任何情况下都是这样。地球可能会因为冷却而

收缩，可能会因为落在其表面的陨石层而增大，它的公转速度可能会逐渐减缓，尽管这样地球仍然和以前一样是一个星球。但是，如果一个分子（如氢分子）的质量或者振动周期发生轻微的变化，那么它将不再是氢分子。因此，如果我们想要得到绝对永恒的长度、时间和质量基准，就不能在行星的尺寸、运动和质量中寻找答案，而只能在这些不灭、不变，并且完全相同的分子的波长、振动周期和绝对质量中寻求。当我们发现在地球上和星空中存在无数质量完全相同的小物体以及无数周期完全相同的振动，并且到目前为止，没有任何自然力可以使它们之中任何一个的质量或者周期发生丝毫的改变，我们似乎是沿着自然知识的道路向那些观点中的一点前进的。从这种观点来看，我们必须接受这种信仰的指引，通过这个信仰我们明白了“我们看见的事物并不是由可见的事物组成的”。分子科学进程中最显著的成就之一就是不可逆过程（一种一直向特定最终状态发展，从不偏离的过程）本质的解释。因此，如果将两种气体装入同一个容器中，它们会混合在一起，并且混合得越来越均匀。如果将两部分温度不同的同种气体装入这个容器中，类似的过程将会发生，容器中的气体将趋于相同的温度。如果两块温度不同的固体相互接触，它们的温度将会向着一个中间的温度转变。在有两种气体的例子中，可以通过化学方法将混合在一起的两种气体再次分开，但是在另外两种情况中，不可能通过任何自然方法将系统再恢复到初始状态。热传导或热扩散过程不仅是不可逆的，而且还伴随着可以转变为机械能的储热的不可逆减少。这就是汤姆孙的能量不可逆损耗理论，它等价于克劳修斯的熵增加理论。这一过程的不可逆性显著地体现在傅立叶的热传导理论中，其方程本身就表明了热扩散达到均匀状态所需时间的所有可能的正值解。然而，如果我们试图通过给符号赋予不断减小的值来增大时间的流动，便会得到事物的一个状态，在这个状态中，公式具有所谓的临界值。而如果我们研究这个状态之前的一个状态，就会发现这个公式变得很荒谬。因此，我们得出这样的观点：事物的状态并不能看作是前一状态的物理结果。我们还发现临界状态实际上并不存在于过去的一个时期，而是被一个有限的间隔与现在的时间分开。这个新起点的观念是最近物理研究带给我们的，是任何之前的具有科学思维的观察者所不能想象的。但是人类的思维并不像傅立叶的热体那样，一直向着完全均匀的最终状态发展，而我们已经可以预测这个状态的性质。这就好像一棵树伸展枝杈，去适应一片新的生长天空，而根则在陌生的地层中委屈

自身，因为那才是它们钻研的目标。对于我们这些只呼吸同龄人的精神、只知道当代思维特征的人，是不可能预言未来科学的普遍状况和特别发现的。物理研究不断向我们揭示自然过程的新性质，这也迫使我们寻求可以适应这些性质的新的思维方式。因此，对数学和物理学之间关系的细致研究的重要性在于可以决定从物理的一个领域推导出的观点被安全地用于将在新领域中使用而形成的观点。通过演讲或者思考中的符号，我们可以将一门熟悉的科学中的语言和观点迁移到我们认识较少的科学中，这些符号可以称为科学比喻。因此，速度、动量、力这些词在基础动力学中获得了特定的精确含义。它们也被用在连通系统的动力学中，虽然与其基本含义完全类似，但却有了更加广泛和普遍的意义。这些基本概念的推广形式可以称之为比喻性的词汇，因为其中每一个抽象词汇都是比喻的。比喻这个真正科学系统的特征就是比喻时所用到的每一个词都保留着自己在最初被使用的时候与系统中其他词汇之间的形式关系。这样，这种方法是真正科学的，即，不仅是科学合法的产物，而且能够继续产生科学。一些电现象之间的相互联系和动力学现象之间的相互联系具有相同的形式。在作出恰当区分和提出临时条件后，将这些动力学词汇应用到电现象中就是一个大胆的比喻的例子，但是如果能够向受过动力学方面培训的人传达真正的电学关系，这就是一个合理的比喻。假设我们通过比喻的方式，成功地将某些属于一门基础科学的观点引入到某类新现象，那么旧观点在新课题上的应用能在多大程度上被当作新现象在物理上与旧观点相似的证据，这就成了一个重要的哲学问题。解决这一问题的最好例子就是，对于同种事物存在两种不同的解释。最著名的当属光的粒子理论和波动理论了。在某些情况下，光现象可以用两种理论很好地解释，而在这些情况之外，其中一种理论就会失效。为了理解两种理论在它们同样适用的领域中的真正关系，我们必须看到哈密顿对它们作出的解释，他发现任何瞬时问题都相应于一个自由运动问题，虽然这个自由运动问题会涉及到不同的速度和时间，但是会导致相同的几何路径。泰特教授曾经写了一篇关于这个主题的有趣的论文。根据一个在德国取得重大进步的电学理论，两个带电粒子会相隔一定距离直接相互作用，但是据韦伯所说，相互作用力取决于它们的相对速度，而根据高斯提出并由黎曼、洛伦茨和纽曼发展的理论，相互作用不是即时的，而是发生在由距离决定的一段时间之后。为了得到认同，这些杰出的研究者所支持的这一理论解释每一种电学现象的能力必须得

到验证。另一种我更喜欢的电学理论，否认相隔一定距离的相互作用，它将电作用归因于扩散介质中的张力和压力，这些应力与工程师所熟悉的力属于相同的类型，而其中的介质与光传播的介质一样。这两种理论不仅能够解释那些它们最初建立时要解释的现象，还能够解释一些没有想到或者现在还不知道的现象，并且这些理论都各自独立地根据电学量得到了相同的光的绝对速度的数值结果。其实这些看上去完全相反的理论，在很大程度上都是真实的，我们只有在达到可以看清不同假说之间的真实关系的科学高度时，才能理解其中的哲学价值。 英文

我应该再次强调数学和物理学之间的关系。就它们本身而言，一个是大脑的运算，另一个是分子的舞蹈。分子有其自身的法则，我们只是选择其中一些最容易的去理解和计算。我们根据这些片面的数据建立理论，还将任何偏离这个理论的实际现象归因于干扰因素。同时，我们也承认所谓的干扰因素只是真实环境中我们不知道或者已经忽略的那部分，并且在将来我们会努力对这些因素进行全面考虑。因此，我们认识到，所谓的干扰仅仅是大脑的虚构，而不是自然事实，在自然作用中不存在干扰。然而，这并不是大脑运算中物质受干扰的唯一途径。数学家的大脑受到很多干扰因素的支配，如疲劳、失忆和犹豫，并且人们发现数学家会因为这些或其他因素犯错。我并不准备否认，对于那些比我们高级的大脑，这些错误都会被归咎于实际思维法则的规则运算。实际上，我们自身也会经常发现，不只是计算的错误，还有导致这些错误发生的原因。然而，这决不会改变我们的判断：它们是错误，一种思维过程是正确的，而另一种则是错误的。我们这个时代最深奥的数学家和思想家——已故的乔治·布尔，当他考虑到正确思维（相对于极其复杂的，虽然可能是同等正确的，真实的且易错的思维来说），其法则的精确性和近乎数学性时，也被引向了另一种观点，这种观点中科学似乎寻求一个不属于她的区域。“我们必须承认，”他说，“确实存在（思维的）法则，即使是它们严格的数学形式也没能免于被破坏。我们必须把它们归因于权威，这个原因的本质并不在于力量，神圣不可破坏的自然界秩序的类比不会帮助我们理解至高法则。” 英文

（王耀杨 翻译；江丕栋 审稿）

On Colour Vision*

J. C. Maxwell

Among the lesser known scientific contributions of James Clerk Maxwell is his work on colour theory. Maxwell showed how three primary colours of light—red, green and blue—can be mixed to generate almost any colour, paving the way for colour photography and projection. In this contribution based on a talk at London's Royal Institution, he reviews this work and expands on its implications for colour vision. Thomas Young had proposed in 1801 that this involved three kinds of light receptor in the eye. Maxwell shows that these receptors have now been identified as rod- and cone-shaped cells in the retina. The existence of three distinct types of colour-sensitive cone cells had not yet been proven, but Maxwell clearly suspects it. [中文](#)

ALL vision is colour vision, for it is only by observing differences of colour that we distinguish the forms of objects. I include differences of brightness or shade among differences of colour. [中文](#)

It was in the Royal Institution, about the beginning of this century, that Thomas Young made the first distinct announcement of that doctrine of the vision of colours which I propose to illustrate. We may state it thus:—We are capable of feeling three different colour-sensations. Light of different kinds excites these sensations in different proportions, and it is by the different combinations of these three primary sensations that all the varieties of visible colour are produced.

In this statement there is one word on which we must fix our attention. That word is, Sensation. It seems almost a truism to say that colour is a sensation; and yet Young, by honestly recognising this elementary truth, established the first consistent theory of colour. So far as I know, Thomas Young was the first who, starting from the well-known fact that there are three primary colours, sought for the explanation of this fact, not in the nature of light, but in the constitution of man. Even of those who have written on colour since the time of Young, some have supposed that they ought to study the properties of pigments, and others that they ought to analyse the rays of light. They have sought for a knowledge of colour by examining something in external nature—something out of ourselves. 中文

Now, if the sensation which we call colour has any laws, it must be something in our own nature which determines the form of these laws; and I need not tell you that the only evidence we can obtain respecting ourselves is derived from consciousness. 中文

The science of colour must therefore be regarded as essentially a mental science. It differs from the greater part of what is called mental science in the large use which it makes of the physical sciences, and in particular of optics and anatomy. But it gives evidence that it is a mental science by the numerous illustrations which it furnishes of various operations of the mind. 中文

In this place we always feel on firmer ground when we are dealing with physical science. I shall therefore begin by showing how we apply the discoveries of Newton to the manipulation of light, so as to give you an opportunity of feeling for yourselves the different sensations of colour. 中文

Before the time of Newton, white light was supposed to be of all known things the purest. When light appears coloured, it was supposed to have become contaminated by coming into contact with

gross bodies. We may still think white light the emblem of purity, though Newton has taught us that its purity does not consist in simplicity. [中文](#)

We now form the prismatic spectrum on the screen. These are the simple colours of which white light is always made up. We can distinguish a great many hues in passing from the one end to the other; but it is when we employ powerful spectroscopes, or avail ourselves of the labours of those who have mapped out the spectrum, that we become aware of the immense multitude of different kinds of light, every one of which has been the object of special study. Every increase of the power of our instruments increases in the same proportion the number of lines visible in the spectrum. [中文](#)

All light, as Newton proved, is composed of these rays taken in different proportions. Objects which we call coloured when illuminated by white light, make a selection of these rays, and our eyes receive from them only a part of the light which falls on them. But if they receive only the pure rays of a single colour of the spectrum, they can appear only of that colour. If I place a disc containing alternate quadrants of red and green paper in the red rays, it appears all red, but the red quadrants brightest. If I place it in the green rays both papers appear green, but the red paper is now the darkest. This, then, is the optical explanation of the colours of bodies when illuminated with white light. They separate the white light into its component parts, absorbing some and scattering others. [中文](#)

Here are two transparent solutions. One appears yellow, it contains bichromate of potash; the other appears blue, it contains sulphate of copper. If I transmit the light of the electric lamp through the two solutions at once, the spot on the screen appears green. By means of the spectrum we shall be able to explain this. The yellow solution cuts off the blue end of the spectrum, leaving only the red, orange, yellow, and green. The blue solution cuts off the red end, leaving only the

green, blue, and violet. The only light which can get through both is the green light, as you see. In the same way most blue and yellow paints, when mixed, appear green. The light which falls on the mixture is so beaten about between the yellow particles and the blue, that the only light which survives is the green. But yellow and blue light when mixed do not make green, as you will see if we allow them to fall on the same part of the screen together. 中文

It is a striking illustration of our mental processes that many persons have not only gone on believing, on the evidence of the mixture of pigments, that blue and yellow make green, but that they have even persuaded themselves that they could detect the separate sensations of blueness and of yellowness in the sensation of green. 中文

We have availed ourselves hitherto of the analysis of light by coloured substances. We must now return, still under the guidance of Newton, to the prismatic spectrum. Newton not only

Untwisted all the shining robe of day,

but showed how to put it together again. We have here a pure spectrum, but instead of catching it on a screen, we allow it to pass through a lens large enough to receive all the coloured rays. These rays proceed, according to well-known principles in optics, to form an image of the prism on a screen placed at the proper distance. This image is formed by rays of all colours, and you see the result is white. But if I stop any of the coloured rays, the image is no longer white, but coloured; and if I only let through rays of one colour, the image of the prism appears of that colour. 中文

I have here an arrangement of slits by which I can select one, two, or three portions of the light of the spectrum, and allow them to form an image of the prism while all the rest are stopped. This gives me a perfect command of the colours of the spectrum, and I can produce on the screen every possible shade of colour by adjusting the breadth and

the position of the slits through which the light passes. I can also, by interposing a lens in the passage of the light, show you a magnified image of the slits, by which you will see the different kinds of light which compose the mixture. 中文

The colours are at present red, green, and blue, and the mixture of the three colours is, as you see, nearly white. Let us try the effect of mixing two of these colours. Red and blue form a fine purple or crimson, green and blue form a sea-green or sky-blue, red and green form a yellow. 中文

Here again we have a fact not universally known. No painter, wishing to produce a fine yellow, mixes his red with his green. The result would be a very dirty drab colour. He is furnished by nature with brilliant yellow pigments, and he takes advantage of these. When he mixes red and green paint, the red light scattered by the red paint is robbed of nearly all its brightness by getting among particles of green, and the green light fares no better, for it is sure to fall in with particles of red paint. But when the pencil with which we paint is composed of the rays of light, the effect of two coats of colour is very different. The red and the green form a yellow of great splendour, which may be shown to be as intense as the purest yellow of the spectrum. 中文

I have now arranged the slits to transmit the yellow of the spectrum. You see it is similar in colour to the yellow formed by mixing red and green. It differs from the mixture, however, in being strictly homogeneous in a physical point of view. The prism, as you see, does not divide it into two portions as it did the mixture. Let us now combine this yellow with the blue of the spectrum. The result is certainly not green; we may make it pink if our yellow is of a warm hue, but if we choose a greenish yellow we can produce a good white.

中文

You have now seen the most remarkable of the combinations of

colours—the others differ from them in degree, not in kind. I must now ask you to think no more of the physical arrangements by which you were enabled to see these colours, and to concentrate your attention upon the colours you saw, that is to say, on certain sensations of which you were conscious. We are here surrounded by difficulties of a kind which we do not meet with in purely physical inquiries. We can all feel these sensations, but none of us can describe them. They are not only private property, but they are incommunicable. We have names for the external objects which excite our sensations, but not for the sensations themselves. [中文](#)

When we look at a broad field of uniform colour, whether it is really simple or compound, we find that the sensation of colour appears to our consciousness as one and indivisible. We cannot directly recognise the elementary sensations of which it is composed, as we can distinguish the component notes of a musical chord. A colour, therefore, must be regarded as a single thing, the quality of which is capable of variation. [中文](#)

To bring a quality within the grasp of exact science, we must conceive it as depending on the values of one or more variable quantities, and the first step in our scientific progress is to determine the number of these variables which are necessary and sufficient to determine the quality of a colour. We do not require any elaborate experiments to prove that the quality of colour can vary in three and only in three independent ways. [中文](#)

One way of expressing this is by saying, with the painters, that colour may vary in hue, tint, and shade. [中文](#)

The finest example of a series of colours varying in hue, is the spectrum itself. A difference in hue may be illustrated by the difference between adjoining colours in the spectrum. The series of hues in the spectrum is not complete; for, in order to get purple hues,

we must blend the red and the blue. 中文

Tint may be defined as the degree of purity of a colour. Thus, bright yellow, buff, and cream-colour, form a series of colours of nearly the same hue, but varying in tint. The tints corresponding to any given hue form a series, beginning with the most pronounced colour, and ending with a perfectly neutral tint. 中文

Shade may be defined as the greater or less defect of illumination. If we begin with any tint of any hue, we can form a gradation from that colour to black, and this gradation is a series of shades of that colour. Thus we may say that brown is a dark shade of orange. 中文

The quality of a colour may vary in three different and independent ways. We cannot conceive of any others. In fact, if we adjust one colour to another, so as to agree in hue, in tint, and in shade, the two colours are absolutely indistinguishable. There are therefore three, and only three, ways in which a colour can vary. 中文

I have purposely avoided introducing at this stage of our inquiry anything which may be called a scientific experiment, in order to show that we may determine the number of quantities upon which the variation of colour depends by means of our ordinary experience alone. 中文

Here is a point in this room: if I wish to specify its position. I may do so by giving the measurements of three distances—namely, the height above the floor, the distance from the wall behind me, and the distance from the wall at my left hand. 中文

This is only one of many ways of stating the position of a point, but it is one of the most convenient. Now, colour also depends on three things. If we call these the intensities of the three primary colour sensations, and if we are able in any way to measure these three intensities, we may consider the colour as specified by these three

measurements. Hence the specification of a colour agrees with the specification of a point in the room in depending on three measurements. [中文](#)

Let us go a step farther, and suppose the colour sensations measured on some scale of intensity, and a point found for which the three distances, or co-ordinates, contain the same number of feet as the sensations contain degrees of intensity. Then we may say, by a useful geometrical convention, that the colour is represented to our mathematical imagination by the point so found in the room; and if there are several colours, represented by several points, the chromatic relations of the colours will be represented by the geometrical relations of the points. This method of expressing the relations of colours is a great help to the imagination. You will find these relations of colours stated in an exceedingly clear manner in Mr. Benson's "Manual of Colour", one of the very few books on colour in which the statements are founded on legitimate experiments. [中文](#)

There is a still more convenient method of representing the relations of colours, by means of Young's triangle of colours. It is impossible to represent on a plane piece of paper every conceivable colour, to do this requires space of three dimensions. If, however, we consider only colours of the same shade, that is, colours in which the sum of the intensities of the three sensations is the same, then the variations in tint and in hue of all such colours may be represented by points on a plane. For this purpose we must draw a plane cutting off equal lengths from the three lines representing the primary sensations. The part of this plane within the space in which we have been distributing our colours will be an equilateral triangle. The three primary colours will be at the three angles, white or gray will be in the middle, the tint or degree of purity of any colour will be expressed by its distance from the middle point, and its hue will depend on the angular position of the line which joins it with the middle point. [中文](#)

Thus the ideas of tint and hue can be expressed geometrically on Young's triangle. To understand what is meant by shade, we have only to suppose the illumination of the whole triangle increased or diminished, so that by means of this adjustment of illumination Young's triangle may be made to exhibit every variety of colour. If we now take any two colours in the triangle and mix them in any proportions, we shall find the resultant colour in the line joining the component colours at the point corresponding to their centre of gravity. 中文

I have said nothing about the nature of the three primary sensations, or what particular colours they most resemble. In order to lay down on paper the relations between actual colours, it is not necessary to know what the primary colours are. We may take any three colours, provisionally, as the angles of a triangle, and determine the position of any other observed colour with respect to these, so as to form a kind of chart of colours. 中文

Of all colours which we see, those excited by the different rays of the prismatic spectrum have the greatest scientific importance. All light consists either of some one kind of these rays, or of some combination of them. The colours of all natural bodies are compounded of the colours of the spectrum. If, therefore, we can form a chromatic chart of the spectrum, expressing the relations between the colours of its different portions, then the colours of all natural bodies will be found within a certain boundary on the chart defined by the positions of the colours of the spectrum. 中文

But the chart of the spectrum will also help us to the knowledge of the nature of the three primary sensations. Since every sensation is essentially a positive thing, every compound colour-sensation must be within the triangle of which the primary colours are the angles. In particular, the chart of the spectrum must be entirely within Young's triangle of colours, so that if any colour in the spectrum is identical

with one of the colour-sensations, the chart of the spectrum must be in the form of a line having a sharp angle at the point corresponding to this colour. [中文](#)

I have already shown you how we can make a mixture of any three of the colours of the spectrum, and vary the colour of the mixture by altering the intensity of any of the three components. If we place a compound colour side by side with any other colour, we can alter the compound colour till it appears exactly similar to the other. This can be done with the greatest exactness when the resultant colour is nearly white. I have therefore constructed an instrument which I may call a colour-box, for the purpose of making matches between two colours. It can only be used by one observer at a time, and it requires daylight, so I have not brought it with me to-night. It is nothing but the realisation of the construction of one of Newton's propositions in his "*Lectioes Opticae*", where he shows how to take a beam of light, to separate it into its components, to deal with these components as we please by means of slits, and afterwards to unite them into a beam again. The observer looks into the box through a small slit. He sees a round field of light, consisting of two semicircles divided by a vertical diameter. The semicircle on the left consists of light which has been enfeebled by two reflexions at the surface of glass. That on the right is a mixture of colours of the spectrum, the positions and intensities of which are regulated by a system of slits. [中文](#)

The observer forms a judgment respecting the colours of the two semicircles. Suppose he finds the one on the right hand redder than the other, he says so, and the operator, by means of screws outside the box, alters the breadth of one of the slits, so as to make the mixture less red; and so on, till the right semicircle is made exactly of the same appearance as the left, and the line of separation becomes almost invisible. [中文](#)

When the operator and the observer have worked together for some

time they get to understand each other, and the colours are adjusted much more rapidly than at first. 中文

When the match is pronounced perfect, the positions of the slits, as indicated by a scale, are registered, and the breadth of each slit is carefully measured by means of a gauge. The registered result of an observation is called a “colour equation”. It asserts that a mixture of three colours is, in the opinion of the observer (whose name is given), identical with a neutral tint, which we shall call Standard White. Each colour is specified by the position of the slit on the scale, which indicates its position in the spectrum, and by the breadth of the slit, which is a measure of its intensity. 中文

In order to make a survey of the spectrum we select three points for purposes of comparison, and we call these the three Standard Colours. The standard colours are selected on the same principles as those which guide the engineer in selecting stations for a survey. They must be conspicuous and invariable, and not in the same straight line.

中文

In the chart of the spectrum you may see the relations of the various colours of the spectrum to the three standard colours, and to each other. It is manifest that the standard green which I have chosen cannot be one of the true primary colours, for the other colours do not all lie within the triangle formed by joining them. But the chart of the spectrum may be described as consisting of two straight lines meeting in a point. This point corresponds to a green about a fifth of the distance from *b* towards F. This green has a wavelength of about 510 millionths of a millimetre by Ditscheiner’s measure. This green is either the true primary green, or at least it is the nearest approach to it which we can ever see. Proceeding from this green towards the red end of the spectrum, we find the different colours lying almost exactly in a straight line. This indicates that any colour is chromatically equivalent to a mixture of any two colours on opposite sides of it and

in the same straight line. The extreme red is considerably beyond the standard red, but it is in the same straight line, and therefore we might, if we had no other evidence, assume the extreme red as the true primary red. We shall see, however, that the true primary red is not exactly represented in colour by any part of the spectrum. It lies somewhat beyond the extreme red but in the same straight line.

中文

On the blue side of primary green the colour equations are seldom so accurate. The colours, however, lie in a line which is nearly straight. I have not been able to detect any measurable chromatic difference between the extreme indigo and the violet. The colours of this end of the spectrum are represented by a number of points very close to each other. We may suppose that the primary blue is a sensation differing little from that excited by the parts of the spectrum near G. 中文

Now, the first thing which occurs to most people about this result is that the division of the spectrum is by no means a fair one. Between the red and the green we have a series of colours apparently very different from either, and having such marked characteristics that two of them, orange and yellow, have received separate names. The colours between the green and the blue, on the other hand, have an obvious resemblance to one or both of the extreme colours, and no distinct names for these colours have ever become popularly recognised. 中文

I do not profess to reconcile this discrepancy between ordinary and scientific experience. It only shows that it is impossible, by a mere act of introspection, to make a true analysis of our sensations. Consciousness is our only authority; but consciousness must be methodically examined in order to obtain any trustworthy results.

中文

I have here, through the kindness of Professor Huxley, a picture of the

structure upon which the light falls at the back of the eye. There is a minute structure of bodies like rods and cones or pegs, and it is conceivable that the mode in which we become aware of the shapes of things is by a consciousness which differs according to the particular rods on the ends of which the light falls, just as the pattern on the web formed by a Jacquard loom depends on the mode in which the perforated cards act on the system of movable rods in that machine. In the eye we have on the one hand light falling on this wonderful structure, and on the other hand we have the sensation of sight. We cannot compare these two things; they belong to opposite categories. The whole of Metaphysics lies like a great gulf between them. It is possible that discoveries in physiology may be made by tracing the course of the nervous disturbance

Up the fine fibres to the sentient brain;

but this would make us no wiser than we are about those colour-sensations which we can only know by feeling them ourselves. Still, though it is impossible to become acquainted with a sensation by the anatomical study of the organ with which it is connected, we may make use of the sensation as a means of investigating the anatomical structure. 中文

A remarkable instance of this is the deduction of Helmholtz's theory of the structure of the retina from that of Young with respect to the sensation of colour. Yong asserts that there are three elementary sensations of colour; Helmholtz asserts that there are three systems of nerves in the retina, each of which has for its function, when acted on by light or any other disturbing agent, to excite in us one of these three sensations. 中文

No anatomist has hitherto been able to distinguish these three systems of nerves by microscopic observation. But it is admitted in physiology that the only way in which the sensation excited by a particular nerve

can vary is by degrees of intensity. The intensity of the sensation may vary from the faintest impression up to an insupportable pain; but whatever be the exciting cause, the sensation will be the same when it reaches the same intensity. If this doctrine of the function of a nerve be admitted, it is legitimate to reason from the fact that colour may vary in three different ways, to the inference that these three modes of variation arise from the independent action of three different nerves or sets of nerves. [中文](#)

Some very remarkable observations on the sensation of colour have been made by M. Sigmund Exner in Prof. Helmholtz's physiological laboratory at Heidelberg. While looking at an intense light of a brilliant colour, he exposed his eye to rapid alternations of light and darkness by waving his fingers before his eyes. Under these circumstances a peculiar minute structure made its appearance in the field of view, which many of us may have casually observed. M. Exner states that the character of this structure is different according to the colour of the light employed. When red light is used a veined structure is seen; when the light is green, the field appears covered with minute black dots, and when the light is blue, spots are seen, of a larger size than the dots in the green, and of a lighter colour. [中文](#)

Whether these appearances present themselves to all eyes, and whether they have for their physical cause any difference in the arrangement of the nerves of the three systems in Helmholtz's theory I cannot say, but I am sure that if these systems of nerves have a real existence, no method is more likely to demonstrate their existence than that which M. Exner has followed. [中文](#)

Colour Blindness

The most valuable evidence which we possess with respect to colour vision is furnished to us by the colour-blind. A considerable number of persons in every large community are unable to distinguish between

certain pairs of colours which to ordinary people appear in glaring contrast. Dr. Dalton, the founder of the atomic theory of chemistry, has given us an account of his own case. [中文](#)

The true nature of this peculiarity of vision was first pointed out by Sir John Herschel in a letter written to Dalton in 1832, but not known to the world till the publication of “Dalton’s Life” by Dr. Henry. The defect consists in the absence of one of the three primary sensations of colour. Colour-blind vision depends on the variable intensities of two sensations instead of three. The best description of colour-blind vision is that given by Prof. Pole in his account of his own case in the “Phil. Trans.”, 1859. [中文](#)

In all cases which have been examined with sufficient care, the absent sensation appears to resemble that which we call red. The point P on the chart of the spectrum represents the relation of the absent sensation to the colours of the spectrum, deduced from observations with the colour box furnished by Prof. Pole. [中文](#)

If it were possible to exhibit the colour corresponding to this point on the chart, it would be invisible, absolutely black, to Prof. Pole. As it does not lie within the range of the colours of the spectrum we cannot exhibit it; and, in fact, colour-blind people can perceive the extreme end of the spectrum which we call red, though it appears to them much darker than to us, and does not excite in them the sensation which we call red. In the diagram of the intensities of the three sensations excited by different parts of the spectrum, the upper figure, marked P, is deduced from the observations of Prof. Pole; while the lower one, marked K, is founded on observations by a very accurate observer of the normal type. [中文](#)

The only difference between the two diagrams is that in the upper one the red curve is absent. The forms of the other two curves are nearly the same for both observers. We have great reason therefore to

conclude that the colour sensations which Prof. Pole sees are what we call green and blue. This is the result of my calculations; but Prof. Pole agrees with every other colour-blind person whom I know in denying that green is one of his sensations. The colour-blind are always making mistakes about green things and confounding them with red. The colours they have no doubts about are certainly blue and yellow, and they persist in saying that yellow, and not green, is the colour which they are able to see. [中文](#)

To explain this discrepancy we must remember that colour-blind persons learn the names of colours by the same method as ourselves. They are told that the sky is blue, that grass is green, that gold is yellow, and that soldiers' coats are red. They observe difference in the colours of these objects, and they often suppose that they see the same colours as we do, only not so well. But if we look at the diagram we shall see that the brightest example of their second sensation in the spectrum is not in the green, but in the part which we call yellow, and which we teach them to call yellow. The figure of the spectrum below Prof. Pole's curves is intended to represent to ordinary eyes what a colour-blind person would see in the spectrum. I hardly dare to draw your attention to it, for if you were to think that any painted picture would enable you to see with other people's vision I should certainly have lectured in vain. [中文](#)

On the Yellow Spot

Experiments on colour indicate very considerable differences between the vision of different persons, all of whom are of the ordinary type. A colour, for instance, which one person on comparing it with white will pronounce pinkish, another person will pronounce greenish. This difference, however, does not arise from any diversity in the nature of the colour sensations in different persons. It is exactly of the same kind as would be observed if one of the persons wore yellow spectacles. In fact, most of us have near the middle of the retina a

yellow spot through which the rays must pass before they reach the sensitive organ: this spot appears yellow because it absorbs the rays near the line F, which are of a greenish-blue colour. Some of us have this spot strongly developed. My own observations of the spectrum near the line F are of very little value on this account. I am indebted to Professor Stokes for the knowledge of a method by which any one may see whether he has this yellow spot. It consists in looking at a white object through a solution of chloride of chromium, or at a screen on which light which has passed through this solution is thrown. This light is a mixture of red light with the light which is so strongly absorbed by the yellow spot. When it falls on the ordinary surface of the retina it is of a neutral tint, but when it falls on the yellow spot only the red light reaches the optic nerve, and we see a red spot floating like a rosy cloud over the illuminated field. 中文

Very few persons are unable to detect the yellow spot in this way. The observer K, whose colour equations have been used in preparing the chart of the spectrum, is one of the very few who do not see everything as it through yellow spectacles. As for myself, the position of white light in the chart of the spectrum is on the yellow side of true white even when I use the outer parts of the retina; but as soon as I look direct at it, it becomes much yellower, as is shown by the point W C. It is a curious fact that we do not see this yellow spot on every occasion, and that we do not think white objects yellow. But if we wear spectacles of any colour for some time, or if we live in a room lighted by windows all of one colour, we soon come to recognise white paper as white. This shows that it is only when some alteration takes place in our sensations that we are conscious of their quality.

中文

There are several interesting facts about the colour sensation which I can only mention briefly. One is that the extreme parts of the retina are nearly insensible to red. If you hold a red flower and a blue flower

in your hand as far back as you can see your hand, you will lose sight of the red flower, while you still see the blue one. Another is, that when the light is diminished red objects become darkened more in proportion than blue ones. The third is, that a kind of colour blindness in which blue is the absent sensation can be produced artificially by taking doses of santonine. This kind of colour blindness is described by Dr. Edmund Rose, of Berlin. It is only temporary, and does not appear to be followed by any more serious consequences than headaches. I must ask your pardon for not having undergone a course of this medicine, even for the sake of becoming able to give you information at first hand about colour-blindness. [中文](#)

(4, 13-16; 1871)

* Lecture delivered before the Royal Institution, March. 24th.

论色觉*

麦克斯韦

詹姆斯·克拉克·麦克斯韦在颜色理论方面的研究是其不太著名的科学贡献之一。早先，麦克斯韦就向人们展示了如何通过混合光的三原色（红、绿、蓝）来得到几乎所有的颜色，这为彩色照相技术和投影技术铺平了道路。在这篇以一次在伦敦皇家研究院所作的报告为基础而形成的文稿中，麦克斯韦回顾了这项研究工作并进一步阐述了其对色觉的意义。1801年，托马斯·杨就提出眼睛中有三种光感受体。麦克斯韦在这里指出，人们已经确认这些光感受体就是视网膜上的杆状细胞和锥形细胞。尽管当时还没有证实存在三种不同类型的对颜色敏感的锥形细胞，但麦克斯韦仍然明确地支持这种猜想。

英文

所有的视觉都是色觉，因为我们只有通过观察颜色的差别才能区分物体的形态。我把明暗的区别也包含在了颜色的区别当中。

英文

约在本世纪初，托马斯·杨在皇家研究院第一次明确地宣布了这个关于色觉的学说，这里，我将要对它进行阐述。我们可以这样来表述：我们能够体验到三种不同的颜色感觉。不同类型的光会以不同比例激发三种颜色感觉，所有可见的颜色就是由这三种基本感觉经过不同的组合而形成的。在这里，有一个词是值得我们注意的，那就是“感觉”。说颜色是一种感觉简直就是一个起码的常识；但杨真正确认了这个基本事实，首先建立了与之一致的关于颜色的理论。据我所知，托马斯·杨是第一个从人类的知觉而不是从光的本质来解释众所周知的三原色的人。即便是那些在杨以后撰写了有关颜色的著作的人们，不是认为应该去研究颜料的特性就是认为应该去分析光线。他们试图用人类自身之外的那些外在本质来揭示颜色的奥秘。

英文

现在，如果说我们称之为颜色的这种感觉遵循某种规律的话，那么一定是我们自身的本质决定了这种规律的形式。无需由我来告诉你，我们所能获得的关于自身的唯一证据就来自于我们的意识。 [英文](#)

因此，色彩学在本质上应该被当作是一种精神科学。它与大多数所谓的精神科学有很大的区别，它要用到物理学，特别是要用到光学和解剖学。但是，种种精神活动提供了大量的例证，可以证明色彩学是一种精神科学。 [英文](#)

当我们利用物理学来处理这一问题的时候，总是感到有更坚实的理论基础。因此，我将从说明我们如何把牛顿的发现运用于光线的操控入手，以此给你一个机会，让你知道你对颜色的不同感觉。 [英文](#)

在牛顿之前，白光被认为是所有已知物质中最纯粹的物质。有色光被认为是白光接触到物体而受到了污染。我们也许仍然可以认为白光象征着纯粹，但是牛顿已经告诉我们，白光的纯粹并不意味着简单。

[英文](#)

现在，我们在屏幕上呈现棱镜光谱，得到的就是构成白光的基本颜色。当我们从一端向另一端观察的时候，可以分辨出很多不同的色彩；但是当我们使用功能更为强大的分光镜，或者利用别人已经制好的光谱时，我们就会发现大量不同种类的光线，每一种都值得专门研究。光谱中可分辨谱线数量增加的比例与仪器分辨率提高的比例是一致的。

[英文](#)

牛顿已经证实，所有的光都是由上面所提到的光线以不同的比例组合而成的。当我们所谓的有色物体被白光照亮的时候，它会选择光线，而我们的眼睛能接受到的只是照射在其上的一部分光线。如果物体只被光谱中纯粹的单色光线所照射，那么它就只能呈现出那种颜色。如果我把红纸和绿纸交替放在一个盘子的不同象限里，用红光照射，整个盘子都会呈现出红色，但是红纸所在部分最明亮。如果把盘子放在绿光中，那么红纸和绿纸都会呈现出绿色，但这一次红纸部分是最暗的。这就是物体被白光照射时所呈现的颜色的光学解释。它们把白光拆分成不同的组成部分，然后吸收一部分，反射另外的部分。 [英文](#)

这里有两种透明的溶液。一种是黄色的重铬酸钾溶液，另一种是蓝色的硫酸铜溶液。如果我让电灯发射的光通过这两种溶液，那么投射到屏幕上的是绿色光斑，这可以用光谱来解释。黄色溶液将光谱中的蓝色一端切断，只剩下了红色、橙色、黄色和绿色；蓝色溶液则将光谱中的红色一端切断，只剩下绿色、蓝色和紫色。正如你看到的那样，只有绿色光才能通过两种溶液。同样的道理，蓝色和黄色的颜料混合在一起通常会呈现出绿色。光照射在混合颜料上，黄色和蓝色的颜料颗粒吸收各自范围的光线，只有绿色光线可以反射出来。但是黄光和蓝光却不能混合成绿光，如果我们把它们投射到屏幕上的同一个区域，就可以看出来。

[英文](#)

这是一个与我们的精神活动过程有关的惊人例子：根据颜料混合物的实验结果，许多人不仅相信蓝色加上黄色会呈现绿色，而且还认为自己可以从绿色的视觉感受中分离出黄色和蓝色的部分。

[英文](#)

到目前为止，我们都在用有色的物质来分析光学问题。现在，我们仍然需要按照牛顿的理论回到棱镜光谱上来。牛顿不仅

解开了日光那耀眼的罩袍，

而且还展示了如何把它重新整合起来。我们有一束纯的分光光谱，但没有将它投射到屏幕上，而是让它通过一个足够大的棱镜以便接收各种颜色的光。依照我们熟知的光学原理，这些光线在其前方一定距离处的屏幕上会形成分光光谱的图像。这个图像由各种颜色的光线组成，而你看到的结果是白色的。但如果我挡住任何一种颜色的光，图像将不再是白色的，而是有色的；如果我只让一种颜色的光通过，那么分光光谱的图像上所呈现的就是那种颜色。

[英文](#)

这里，我可以利用设置狭缝的方法选择光谱中的一部分、两部分或三部分光谱线，使其成像，而其他部分则被挡住。这样我就可以极好地控制光谱中的颜色了，通过调整光路中各狭缝的宽度和位置，可以使屏幕上呈现出每一种颜色的图像。我还可以在光路中插入透镜，使你看到狭缝的像，这样你就可以观察到混合在一起的不同种类的光。

[英文](#)

现在，选取红、绿、蓝三种颜色，正如你所见，它们混合在一起后

几乎是白色的。我们也可以尝试一下混合三种当中的任意两种颜色。红色和蓝色形成纯紫色或者深红色，绿色和蓝色形成海绿色或者天蓝色，红色和绿色形成黄色。 [英文](#)

这里，我们又得到了一个并非被广泛了解的事实。没有哪一个画家会用他的红颜料和绿颜料混合在一起调出纯黄色。这样做只能得到一种很脏的灰黄色。他自己本来就有鲜亮的黄颜料，用这个就行了。当他混合红绿两种颜料的时候，红颜料颗粒所反射出来的红光因为被绿颜料颗粒吸收而几乎失去了全部亮度，绿光的情况也好不了多少，因为绿颜料颗粒反射出的绿光也会被红颜料颗粒吸收。但是如果我们作画时所用的笔是由光线组成的，那么涂覆两种颜色得到的效果就会完全不同。红光和绿光会形成非常漂亮的黄色，和光谱中最纯的黄光一样鲜艳。 [英文](#)

我现在调整狭缝，选取光谱中的黄光。你会发现它与红光和绿光混合在一起的颜色非常相似。然而，用物理学的观点来看，它与混合物不同，因为它是严格均质的。正如你所见，棱镜并没有像对待混合光线那样把它分成两部分。让我们把这束黄光和光谱中的蓝光混合起来。结果当然不是绿光；如果采用暖色调的黄光，我们得到的将是粉色，但如果我们选的是偏绿的黄光，就会得到很好的白色。 [英文](#)

你已经看到了一些最显著的颜色组合，其他颜色组合与这些相比只有程度上的差别，而没有本质上的差别。现在，我请你别去考虑那些让你看到颜色的实验装置，而把你的注意力集中在你所看到的颜色上，也就是说，把注意力集中在你的感受上。我们遇到的困难是，我们无法进行纯粹的物理意义上的研究。我们都能感觉得到，但是谁也无法描述这一切。感觉不仅是个人的感受，而且难以表达出来。我们能说出那些刺激我们感受的外部物体的名字，但是无法描述那种感受本身。 [英文](#)

当我们注视一大块均匀的颜色时，不论这种颜色是简单的还是复合的，我们发现在我们的意识中对颜色的感觉是一个不可分割的整体。我们无法像分辨和弦中的音符那样，直接把构成这种感受的元素分离出来。所以颜色应该被看作是一种单一的东西，而它的性质可以改变。

[英文](#)

为了能用精确的科学术语描述一个量，我们必须建立这个量与一个或几个变量之间的依赖关系，我们研究工作的第一步是确定能充分地决定一种颜色性质的变量的数目。我们不需要任何复杂的实验就能证明颜色的性质依赖且只依赖于三个独立的变量。 [英文](#)

画家们对此有一种说法，即颜色之间的区别是：色相、纯度和明度。 [英文](#)

一系列色彩依色相变化的最好例子就是光谱本身。光谱中相邻颜色的差异可以用来说明色相的区别。光谱中的色相系列并不完全；因为要想得到紫色色相，我们必须混合红光和蓝光。 [英文](#)

纯度可以被定义为一种颜色纯净的程度。这样，明黄色、浅黄色和奶黄色形成了一个具有几乎相同色相的系列，但纯度不同。对应于某个给定的色相，纯度不同的一组颜色可以形成一个系列，从最浓的颜色开始，到最淡的颜色结束。 [英文](#)

明度可以被定义为光照程度的多少。如果我们从任意色相的任意纯度出发，就可以在这种颜色和黑色之间形成一个渐变，这个渐变就是这种颜色的一个明度序列。这样，我们就可以说，棕色是橙色明度变暗得到的结果。 [英文](#)

一种颜色的性质可以按三种不同且独立的方式变化。我们想不出任何其他的变化方式。事实上，如果我们将一种颜色调整为另一种颜色，使得前者 and 后者在色相、纯度、明度上都一致，那么这两种颜色绝对没有任何差异。因此一种颜色的变化方式有且只有三种。 [英文](#)

我有意避免在科学实验的层面上去介绍我们的研究，这样做是为了表明，我们仅凭日常经验就可以确定描述颜色变化的变量数目。 [英文](#)

房间里有一个点，如果我想确定这个点的位置，我可以给出三个距离的测量值：即相对于地面的高度、到我身后的墙的距离以及到我左手边的墙的距离。 [英文](#)

这只是描述一个点位置的多种方法中的一种，但它是最方便的一

种。现在，颜色也同样依赖于三个变量。如果我们把这些称作三种原色的感觉强度，并且如果我们能用某种方法测量出这三种强度，那么我们就可以认为颜色能够通过对这三者的测量而被确定下来。因此，描述一种颜色和描述空间某点的位置一样，都要依赖于对三个变量的测量。

英文

让我们再深入一步。假设用强度等级来衡量的色觉所包含的强度数值，与空间中某点所包含的用英尺数表示的三个距离，或三个坐标的数值相同，那么我们就可以说，通过实用几何学的常规做法，我们可以在数学上将色觉想象成空间中的某一点；如果有多种颜色，就用多个点来表示，那么这些颜色之间的关系也可以用点之间的几何学关系来描述。这样的描述对于我们想象不同颜色之间的关系大有帮助。在本森先生所著的《颜色手册》一书中，你会发现颜色之间的这些关系被叙述得非常清晰。基于正规实验的关于颜色方面的著作少之又少，而这本书就是其中之一。

英文

还有一种更方便的描述颜色之间关系的方法，即杨的颜色三角形法。我们无法在一张纸的平面上描述任何一种可见的颜色，要做到这一点需要三维的空间。但是，如果我们只考虑具有相同明度的颜色，也就是说，在这些颜色中三种色觉的强度之和是一样的，那么纯度和色相的变化就可以用平面上的点来描述了。为此，我们用三条等长的、代表原色感觉的线来切割一个平面。它们所围的区域是一个等边三角形，我们将在这个区域中分配我们的颜色。三种原色将位于三个顶角，中间是白色或者灰色，颜色的纯度用这种颜色到中点的距离来表示，颜色的色相则取决于它与中点连线的角度。

英文

这样，纯度和色相就可以利用杨氏三角形得到一个几何上的描述。为了理解明度的含义，我们只需增加或者减弱整个三角的照明度就可以了。因此用调整照明度的方法，杨氏三角形可以表示所有的颜色。如果我们从杨氏三角形中选取任意两种颜色，然后把二者以任意比例混合在一起，混合后的颜色对应于这两种颜色连线上重心的位置。

英文

我没有做任何有关三种原色感觉本质的说明，也没有说它们与哪些颜色更接近。要在本文中解释清楚实际颜色之间的关系，不需要知道三

原色到底是什么。我们可以选取任意的三种颜色，暂且把它们放在杨氏三角形的三个顶点上，然后就可以确定其他可见颜色与它们的相对位置，这样就得到了一种色卡。 [英文](#)

我们见到的所有被分光光谱中的不同光线所激发的颜色在科学上都具有极高的重要性。所有的光都是其中的一种光线，或者是其中几种光线的组合。自然界中实物的颜色都是由光谱中的颜色构成的。因此，如果我们能构造一个光谱的色卡，用颜色的不同位置来表示它们之间的关系，那么，自然界中所有物体的颜色都可以在用光谱中颜色的位置界定的色卡上找到它们的位置。 [英文](#)

色卡还有助于我们了解三原色的本质。由于每一种感觉都是一种实实在在的东西，每一种复合的色觉都必然包含在以三原色为顶角的三角形中。特别是光谱的色卡一定完全包含在杨氏三角形内部，这样，如果光谱中任何一种颜色和某种色觉相一致，那么光谱在杨氏三角形中的形式一定是一条和这种颜色所在的点成很小角度的直线。 [英文](#)

我已经告诉大家怎样将光谱中的任意三种颜色混合，并且用改变颜色三分量中任意一个的强度来改变这种混合的颜色。如果我们把一种混合颜色和另外一种颜色并列在一起，我们可以调整这种混合颜色，直到它和另外一种颜色完全相同为止。当最终要得到的颜色接近白色时，这个过程可以最为精确地完成。于是我构造了一种我称作色箱的装置，用来匹配两种颜色。这个装置每次实验只能允许一个人进行观察，而且需要在日光下进行，所以今晚我没有把它带来。这个装置没什么大不了，只不过实现了牛顿在《光学讲义》中谈到的一个构想而已，牛顿告诉我们如何获得一束光，并将其分离成不同组分，以及如何用狭缝来获取这些组分，然后再把它们重新整合成一束光。观察者通过一个狭缝来观察箱子的内部。他将看到一个圆形的发光区域，一条垂直方向的直径把它分割成左右两个半圆。左边半圆是经过两次镜面反射而减弱的光；右边半圆是由光谱中的颜色混合而成的，其位置和强度都可以通过狭缝来调节。 [英文](#)

观测者将对两边半圆的颜色进行判断。假如他认为右边的光比左边的光更红，那么他就可以让色箱的操作者通过拧紧箱外的螺丝来调节某

个狭缝的宽度，使得混合光线的红色变浅，如此这般，直到左右两个半圆看起来完全相同，中间的分界线几乎看不出来为止。 [英文](#)

操作者和观察者在一起工作过一段时间以后，他们的合作会更加默契，调整颜色的速度也会比初次合作时更快。 [英文](#)

当颜色匹配完成之后，每一个狭缝位置的刻度都被记录下来，狭缝的宽度用刻度尺仔细测量。一次观察的记录结果被称为一个“颜色方程”。它说明观察者（他的名字将被记录下来）认为，三种颜色混合而成的颜色是一种中性色，我们称之为标准白色。每一种颜色在光谱中的位置都由狭缝的位置确定，而狭缝的宽度则表示了它的强度。 [英文](#)

为了考察光谱的特性，我们选择三个点用以比较，我们称它们为三个标准色。标准色的选择原则与工程师选取观测点的原则相同，这些点必须既突出又稳定，且不在同一条直线上。 [英文](#)

在光谱的色卡上，你可以看到光谱中的不同颜色和三个标准色之间的关系，以及不同颜色之间的关系。事实表明，我选择的标准绿色不可能是三原色之一，因为其他颜色并不全在三点之间的区域中。但是光谱色卡可以描述成两条相交的直线。相应的交点对应一种绿色，它到标准绿色的距离为**b**到**F**距离的 $1/5$ 。根据迪特沙纳的测量，这种绿色的波长是510纳米。这种绿色即便不是真正的原色，至少也是我们曾经见到过的最接近原色的颜色。从这种绿色向光谱中的红色一端连线，我们发现不同的颜色几乎都落在了这条直线上。这表明，从色度上来说，任一种颜色都等价于位于该直线两端的两种颜色的混合。极端红色应该在比标准红色更远的位置，但是它与标准红色在同一条直线上，因此，如果没有相反的证据，我们可以将极端红色视为原红。然而，我们可以看到，真正的原红并没有出现在光谱的任何部分。它在比极端红色更远的位置，但仍然在同一条直线上。 [英文](#)

在原绿的蓝端，颜色方程就不是那么精确了。但色点近似分布于一条直线上。我现在还无法测量出极端靛青和紫色的区别。在光谱中这一端的颜色是用许多非常接近的点来表示的。我们可以假设原蓝这种色觉略微区别于由光谱中靠近**G**的部分所激发的感觉。 [英文](#)

现在，面对这样的结果，摆在大家面前的首要问题是，光谱的划分并不公平。红绿之间的一系列颜色都有明显的区别，它们的区分非常明显，以至于黄色和橙色需要有各自不同的名字。反之，绿蓝之间的颜色却与这两种极端颜色或其中之一很相似，这些被广泛认可的颜色也没有自己的名字。 [英文](#)

我并非是要调和这种一般经验和科学实验之间的差异和矛盾。只是事实表明，仅仅用自省的方式不可能对我们的感觉作出正确的分析。感觉是我们唯一的凭据，但是感觉必须经过系统的检验才能得到可靠的结果。 [英文](#)

我从赫胥黎教授那里得到了一张描述光线落在眼睛后部成像的结构图。这里有很多棒状、锥状、钉状的微结构。我们很可能就是通过确定光线到底落在哪些棒状体的末端而感觉到物体的形状的，就像提花织布机织出什么样的花纹取决于打孔卡作用于机器中可移动棒的方式。在眼睛里，一方面光线照射在这种精密的结构之上，另一方面我们有视觉感受。我们无法比较这两个方面，因为它们属于不同的范畴。形而上学就是二者之间的鸿沟。跟踪

从神经纤维到大脑之间

的神经扰动可能会在生理学上得到一些发现；但是，这些对我们关于色觉的认识并没什么帮助，因为我们只能自己去感受颜色。虽然我们不可能通过解剖相关的器官来增加对色觉的了解，但是我们可以利用我们的感觉，把它作为研究组织结构的一种手段。 [英文](#)

这里有一个著名的例子，就是从杨的色觉理论推出亥姆霍兹关于视网膜结构的理论。杨声称有三种基本的色觉；而亥姆霍兹则声称在视网膜里有三种神经系统，每一种系统都有自己的功能，当有光照或者其他扰动作用时，每一种系统都会激发出我们这三种感觉中的一种。 [英文](#)

到目前为止，还没有任何一个解剖学家能够在微观尺度的观察中分辨出这三种神经系统。但是生理学上却认为，由某种神经激发的感觉只能在强度上有所变化。感觉强度的变化可以从最微弱的触感到难以忍受

的疼痛；但不论激发感觉的原因是什么，只要激发的强度相同，那么感受也相同。如果这种神经功能的学说得到认可，那么从颜色能够以三种不同的方式变化这个事实中，就可以推断出这三种不同的色觉模式起源于三种不同的神经或者神经集合。

[英文](#)

在亥姆霍兹教授位于海德堡的生理学实验室里，西格蒙德·埃克斯纳作出了一些非常引人注目的关于色觉的观察结果。当注视一种色彩耀眼的强光时，他不断地在眼前挥动手指，使眼睛迅速地在明亮和黑暗之间切换。在这种情况下，一种奇异的微结构出现在了视野当中，可能很多人都曾偶然发现过这个现象。埃克斯纳声称，该结构的特征随着光源颜色的不同而变化。红光照射时，见到的是叶脉结构；绿光照射时，视野中好像布满了小黑点；蓝光照射时，看到的斑点比绿光中的更大，颜色也更淡。

[英文](#)

我不知道是否每个人都能感受到这些现象，也不知道亥姆霍兹理论中所说的三种神经系统的排布是否会由于个体之间的差异而在不同人中有所不同，但是我确信，如果这样的神经系统真的存在的话，那么埃克斯纳所用的方法就是最好的证明办法。

[英文](#)

色盲

色盲现象为我们提供了关于色觉的最有价值的证据。在每一个大型社区中都有相当多的人无法分辨出在正常人看来区别很明显的一些颜色。化学原子理论的奠基人道尔顿博士本人就为我们提供了例子。

[英文](#)

1832年，约翰·赫歇尔爵士在他写给道尔顿博士的一封信中第一次指出了这种异常色觉现象的本质，但是直到亨利博士出版《道尔顿生平》一书时，这封信的内容才公诸于世。这种缺陷是由于缺少三种原色感觉中的一种而造成的。色盲者的视觉只依赖于两种色觉的强度变化，而不是三种。波尔教授在1859年的《自然科学会报》上给出了他自己的亲身体验，这是迄今为止对色盲现象的最佳描述。

[英文](#)

在所有经过精心检验的例子中，我们发现，那种缺失的色觉好像类似于我们所称的红色。光谱色卡上的P点代表了缺失的色觉和光谱中颜

色的关系，这是根据波尔教授提供的色箱进行观察而推出的结果。

英文

如果可以将色卡上这一点所代表的颜色呈现在波尔教授眼前，那么他将什么也看不见，或者说眼前一片黑暗。由于这种颜色不在光谱的范围之内，所以我们无法将其呈现出来。事实上，色盲者能够看到光谱的红端，尽管他们看到的红色比我们看到的暗很多，因而无法激发出我们正常人所感受到的红色。在由光谱不同部分激发的三种基本色觉的强度图中，上图中标为P的点是从波尔教授的观察结果推导出来的，而下图中标为K的点是一个色觉正常的观察者经过精确实验得到的结果。

英文

两张图之间的唯一区别是，上图中缺少红色的曲线。对这两个观察者来说，另外两条曲线的形状几乎是完全相同的。因此，我们可以非常肯定地说，波尔教授能感受到的颜色是我们所称的绿色和蓝色。这就是我的计算结果，但是波尔教授，还有我认识的其他色盲者都不承认他们能感受到绿色。色盲者经常会把绿色的东西看错或者把红色和绿色搞混。色盲者肯定能看到的颜色是蓝色和黄色，他们坚持认为，他们能看到的颜色是黄色而不是绿色。

英文

要想解释这个矛盾，我们必须知道，色盲者了解颜色名字的方式和我们正常人相同。别人告诉他们，天空是蓝色的，草地是绿色的，金子是黄色的，军装是红色的。他们观察这些物体在颜色上的差别，他们以为他们看到的颜色与我们看到的一样，只是不那么清楚而已。但如果我们看一看这张图，就会发现，在他们的第二种色觉中，最明亮的部分并不是光谱中的绿色，而是我们称为黄色的部分，我们告诉他们这就是黄色。波尔教授所绘曲线下面的光谱图向色觉正常的人展示了一个色盲者的眼睛所看到的光谱。其实我不敢让大家注意它，因为要是你认为自己可以用别人的视觉来看一幅画的话，那我前面所说的就都白费了。

英文

关于黄色斑点

关于颜色的种种实验表明，人与人之间在视觉上的差别很明显，虽

然他们都是视觉正常的人。比如，把一种颜色和白色作比较时，有人认为它偏粉色，有人认为它偏绿色。然而，这种差别并不能说明每个人的色觉有本质上的不同。这就好像有人戴上了黄色眼镜观察事物。事实上，我们中的大多数人在接近视网膜中部的地方都有一个黄色的斑点，光线必须穿过这个黄斑才能到达感觉器官。这个斑点之所以呈现黄色，是因为它吸收了F线附近蓝绿色的光线。有些人的这个斑点非常粗大。由于这个原因，我自己看到的光谱在F线附近的区域就很微弱。我要感谢斯托克斯教授教给我判断一个人是否长有这种黄斑的方法。方法如下：让观察者通过氯化铬溶液观察一个白色物体，或者将一束光透过氯化铬溶液投射到屏幕上，让观察者去看这个屏幕。这束光是由红光和会被黄斑强烈吸收的光混合而成。当这束光线投射到正常人的视网膜上时，看到的会是一种中性色；但当它投射到黄斑上时，只有红光能够到达视神经，于是我们在被照亮的区域将看到一团像红云一般浮动着的红色斑点。

[英文](#)

用这种方法检测发现只有极少数人没有这个黄斑。观察者K，就是其颜色方程曾被用于制作光谱色卡的那位，是极少数不用透过黄色眼镜看世界的人之一。至于我，在我的色卡上，白光的位置在真正的白色偏黄的一侧，即便我用视网膜的外侧观察也是如此；不过，当我直视的时候，我看到的白色位置就更加偏黄了，正如W C点所示。奇怪的是，我们并不是在所有情况下都能看到这个黄斑，而且我们也不会认为白色物体是黄色的。但如果我们戴上任意颜色的眼镜后过一段时间，或者我们所住房间的窗户都是同一种颜色时，我们很快就会认出白纸是白色的。这表明，只有当我们的感觉发生了一些改变的时候，我们才能意识到它们的性质。

[英文](#)

最后，我只能简单介绍几个关于色觉的有趣事例。一个是，视网膜最外面的部分几乎感受不到红色。如果你手里拿着一枝红花和一枝蓝花，然后把手放到你身后几乎看不见的位置，这时你可能就看不见红花了，但仍然能看见蓝花。另一个是，当光减弱的时候，红色物体将比蓝色物体更快地变暗。第三，服用大剂量的山道年能人为地造成一种不能识别蓝色的假性色盲状态。柏林的埃德蒙·罗泽博士谈到过这种色盲。这只是一时暂时的状态，除了头痛以外不会有其他更严重的后果。我必须

请求大家的原谅，因为我没有服用过这种药物，尽管我知道这样做可以给你们提供关于色盲的第一手资料。

英文

（王静 翻译；江丕栋 审稿）

* 这是3月24日向皇家研究院所作的演讲。

The Copley Medalist of 1870

J. Tyndall

James prescott Joule was born in the city of Salford in Lancashire and worked either there or in the adjacent city of Manchester. His scientific work centred on electricity and the rules by which energy of one kind—a current of electricity, for example—may be converted into energy of some other kind (such as mechanical work). Joule is now commemorated by the use of his name as the unit of energy in the MKS system. The Copley medal, which was awarded to Joule in 1870, is the Royal Society's most venerable award. The author of this article, John Tyndall, was a professor at the institution in Manchester that eventually became its first university, but had by 1871 become a professor at the Royal Institution in London. [中文](#)

THIRTY years ago Electro-magnetism was looked to as a motive power which might possibly compete with steam. In centres of industry, such as Manchester, attempts to investigate and apply this power were numerous, as shown by the scientific literature of the time. Among others Mr. James prescott Joule, a resident of Manchester, took up the subject, and in a series of papers published in Sturgeon's "Annals of Electricity" between 1839 and 1841, described various attempts at the construction and perfection of electro-magnetic engines. The spirit in which Mr. Joule pursued these inquiries is revealed in the following extract: "I am particularly

anxious," he says, "to communicate any new arrangement in order, if possible, to forestal the monopolising designs of those who seem to regard this most interesting subject merely in the light of pecuniary speculation." He was naturally led to investigate the laws of electro-magnetic attractions, and in 1840 he announced the important principle that the attractive force exerted by two electro-magnets, or by an electro-magnet and a mass of annealed iron, is directly proportional to the square of the strength of the magnetising current; while the attraction exerted between an electro-magnet and the pole of a permanent steel magnet varies simply as the strength of the current. These investigations were conducted independently of, though a little subsequently to, the celebrated inquiries of Henry, Jacobi, and Lenz and Jacobi on the same subject. [中文](#)

On the 17th of December, 1840, Mr. Joule communicated to the Royal Society a paper on the production of heat by Voltaic electricity; in which he announced the law that the calorific effects of equal quantities of transmitted electricity are proportional to the resistance overcome by the current, whatever may be the length, thickness, shape, or character of the metal which closes the circuit; and also proportional to the square of the quantity of transmitted electricity. This is a law of primary importance. In another paper, presented to but declined by the Royal Society, he confirmed this law by new experiments, and materially extended it. He also executed experiments on the heat consequent on the passage of Voltaic electricity through electrolytes, and found in all cases that the heat evolved by the proper action of any Voltaic current is proportional to the square of the intensity of that current multiplied by the resistance to conduction which it experiences. From this law he deduced a number of conclusions of the highest importance to electro-chemistry. [中文](#)

It was during these inquiries, which are marked throughout by rare sagacity and originality, that the great idea of establishing

quantitative relations between Mechanical Energy and Heat arose and assumed definite form in his mind. In 1843 Mr. Joule read before the meeting of the British Association at Cork a paper "On the Calorific Effects of Magneto-Electricity and on the Mechanical Value of Heat". Even at the present day this memoir is tough reading, and at the time it was written it must have appeared hopelessly entangled. This I should think was the reason why Prof. Faraday advised Mr. Joule not to submit the paper to the Royal Society. But its drift and results are summed up in these memorable words by its author, written some time subsequently: "In that paper it was demonstrated experimentally that the mechanical power exerted in turning a magneto-electric machine is converted into the heat evolved by the passage of the currents of induction through its coils, and on the other hand, that the motive power of the electro-magnetic engine is obtained at the expense of the heat due to the chemical reaction of the battery by which it is worked."* It is needless to dwell upon the weight and importance of this statement. 中文

Considering the imperfections incidental to a first determination, it is not surprising that the "mechanical values of heat," deduced from the different series of experiments published in 1843, varied somewhat widely from each other. The lowest limit was 587, and the highest 1,026 foot-pounds for 1°F of temperature. 中文

One noteworthy result of his inquiries, which was pointed out at the time by Mr. Joule, had reference to the exceedingly small fraction of the heat which is actually converted into useful effect in the steam-engine. The thoughts of the celebrated Julius Robert Mayer, who was then engaged in Germany upon the same question, had moved independently in the same groove; but to his labours due reference will doubtless be made on a future occasion. In the memoir now referred to Mr. Joule also announced that he had proved heat to be evolved during the passage of water through narrow tubes; and he

deduced from these experiments an equivalent of 770 foot-pounds, a figure remarkably near to the one now accepted. A detached statement regarding the origin and convertibility of animal heat strikingly illustrates the penetration of Mr. Joule and his mastery of principles at the period now referred to. A friend had mentioned to him Haller's hypothesis, that animal heat might arise from the friction of the blood in the veins and arteries. "It is unquestionable," writes Mr. Joule, "that heat is produced by such friction, but it must be understood that the mechanical force expended in the friction is a part of the force of affinity which causes the venous blood to unite with oxygen, so that the whole heat of the system must still be referred to the chemical changes. But if the animal were engaged in turning a piece of machinery, or in ascending a mountain, I apprehend that in proportion to the muscular effort put forth for the purpose, a *diminution* of the heat evolved in the system by a given chemical action would be experienced." The italics in this memorable passage, written it is to be remembered in 1843, are Mr. Joule's own. [中文](#)

The concluding paragraph of this British Association paper equally illustrates his insight and precision regarding the nature of chemical and latent heat. "I had," he writes, "endeavoured to prove that when two atoms combine together, the heat evolved is exactly that which would have been evolved by the electrical current due to the chemical action taking place, and is therefore proportional to the intensity of the chemical force causing the atoms to combine. I now venture to state more explicitly, that it is not precisely the attraction of affinity, but rather the mechanical force expended by the atoms in falling towards one another, which determines the intensity of the current, and, consequently, the quantity of heat evolved; so that we have a simple hypothesis by which we may explain why heat is evolved so freely in the combination of gases, and by which indeed we may account 'latent heat' as a mechanical power prepared for action as a watch-spring is when wound up. Suppose, for the sake of illustration,

that 8 lbs. of oxygen and 1 lb. of hydrogen were presented to one another in the gaseous state, and then exploded; the heat evolved would be about 1°F in 60,000 lbs. of water, indicating a mechanical force expended in the combination equal to a weight of about 50,000,000 lbs. raised to the height of one foot. Now if the oxygen and hydrogen could be presented to each other in a liquid state, the heat of combination would be less than before, because the atoms in combining would fall through less space.” No words of mine are needed to point out the commanding grasp of molecular physics, in their relation to the mechanical theory of heat, implied by this statement. 中文

Perfectly assured of the importance of the principle which his experiments aimed at establishing, Mr. Joule did not rest content with results presenting such discrepancies as those above referred to. He resorted in 1844 to entirely new methods, and made elaborate experiments on the thermal changes produced in air during its expansion: firstly, against a pressure, and therefore performing work; secondly, against no pressure, and therefore performing no work. He thus established anew the relation between the heat consumed and the work done. From five different series of experiments he deduced five different mechanical equivalents; the agreement between them being far greater than that attained in his first experiments. The mean of them was 802 foot-pounds. From experiments with water agitated by a paddle-wheel, he deduced, in 1845, an equivalent of 890 foot-pounds. In 1847 he again operated upon water and sperm-oil, agitated them by a paddle-wheel, determined their elevation of temperature, and the mechanical power which produced it. From the one he derived an equivalent of 781.5 foot-pounds; from the other an equivalent of 782.1 foot-pounds. The mean of these two very close determinations is 781.8 foot-pounds. 中文

At this time the labours of the previous ten years had made Mr. Joule

completely master of the conditions essential to accuracy and success. Bringing his ripened experience to bear upon the subject, he executed in 1849 a series of 40 experiments on the friction of water, 50 experiments on the friction of mercury, and 20 experiments on the friction of plates of cast-iron. He deduced from these experiments our present mechanical equivalent of heat, justly recognised all over the world as “Joule’s equivalent”. 中文

There are labours so great and so pregnant in consequences, that they are most highly praised when they are most simply stated. Such are the labours of Mr. Joule. They constitute the experimental foundation of a principle of incalculable moment, not only to the practice, but still more to the philosophy of Science. Since the days of Newton, nothing more important than the theory of which Mr. Joule is the experimental demonstrator has been enunciated. 中文

I have omitted all reference to the numerous minor papers with which Mr. Joule has enriched scientific literature. Nor have I alluded to the important investigations which he has conducted jointly with Sir William Thomson. But sufficient, I think, has been here said to show that, in conferring upon Mr. Joule the highest honour of the Royal Society, the Council paid to genius not only a well-won tribute, but one which had been fairly earned twenty years previously.† 中文

Comparing this brief history with that of the Copley Medalist of 1871, the differentiating influence of “environment” on two minds of similar natural cast and endowment comes up in an instructive manner. Withdrawn from mechanical appliances, Mayer fell back upon reflection, selecting with marvellous sagacity from existing physical data the single result on which could be founded a calculation of the mechanical equivalent of heat. In the midst of mechanical appliances, Joule resorted to experiment, and laid the broad and firm foundation which has secured for the mechanical theory the acceptance it now enjoys. A great portion of Joule’s time was occupied in actual

manipulation; freed from this, Mayer had time to follow the theory into its most abstruse and impressive applications. With their places reversed, however, Joule might have become Mayer, and Mayer might have become Joule. [中文](#)

(5, 137-138; 1871)

* *Phil. Mag.* May 1845.

† Had I found it in time, this notice should have preceded that of the Copley Medalist of 1871.

1870年的科普利奖章获得者

廷德尔

詹姆斯·普雷斯科特·焦耳出生在兰开夏郡的索尔福德，他在他的家乡（或者说曼彻斯特临近的城市）工作。他的研究工作集中在电学和一种能量形式（比如电流）转化成另外的能量形式（比如动能）的规律上。为了纪念焦耳，米-千克-秒单位制系统采用他的名字作为能量单位。1870年，焦耳被授予科普利奖章，这是皇家学会的最高荣誉。这篇文章的作者约翰·廷德尔是曼彻斯特研究所的教授，该研究所最终成为了当地的第一所大学。但在1871年之前作者就已经成为伦敦皇家研究院的一名教授。 [英文](#)

30年前，人们希望电磁能够成为一种可以和蒸汽相媲美的动力形式。在像曼彻斯特那样的工业中心，人们对这种动力的研究和应用十分广泛，这可以从当时的科学文献中看出来。和其他人一样，曼彻斯特人詹姆斯·普雷斯科特·焦耳也研究了这个问题，并于1839~1841年间在斯特金的《电学年鉴》上发表了一系列文章，描述了设计和完善电磁发动机的各种尝试。焦耳先生的探索精神可以从下面的话中体现出来，他说，“我非常急切地要把所有适宜的新成果公之于众，为的是尽量抢在那些仅仅为了金钱而想把这个极为有趣的课题垄断掉的人前面。”他很自然地把研究转向了电磁吸引作用的规律，并在1840年宣布了一个重要的定律：两个电磁体或者电磁体和退火铁之间的吸引力正比于磁化电流强度的平方；电磁体和永磁体磁极之间的相互作用只与电流强度成正比。这些研究是焦耳独立进行的，尽管比亨利、雅各比以及楞次和雅各比通过著名实验得出的相同结果略晚一些。 [英文](#)

1840年12月17日，焦耳先生在皇家学会宣读了他关于伏打电流发热的论文；在论文中，他宣称，等量的传输电流产生的热效应跟电流所

克服的电阻成正比，与闭合电路中金属的长度、厚度、形状和特性无关，并且与电流的平方成正比。这是一个非常重要的定律。在另一篇提交给皇家学会但遭退稿的文章中，焦耳用新的实验证实了这个定律，并将其大大扩展。他还针对伏打电流通过电解液时的热效应进行了实验研究，最终发现，在所有情况下，伏打电流产生的热量都正比于电流强度的平方与电阻的乘积。通过这个定律，他推出了一些在电化学领域极为重要的结论。 [英文](#)

在从事这些充满超人智慧和独创性的研究过程中，焦耳萌生并逐渐形成了在机械能和热量之间建立定量关系的想法。1843年焦耳先生在英国科学促进会于科克召开的会议上宣读了一篇《论磁电的热效应和热的机械值》的论文。即便在今天，这个研究报告都是很难读懂的，在当时要读懂它简直是毫无希望的。我想这就是法拉第教授建议焦耳先生不要将它提交给皇家学会的原因。但隔了一段时间以后，焦耳对文章的主旨和结论作出了如下的概括，给人留下极深的印象：“那篇文章用实验证明了施加于磁电式电机上的机械能被转化成线圈中感应电流所释放的热量，另一方面，电磁发动机的动力则来源于电池化学反应所提供的热量。”*这个结论的重要性和价值也就不必在此赘述了。 [英文](#)

在1843年发表的论文中，一系列实验所得到的“热的机械值”差别较大，考虑到首次得出结论的实验所要面对的各种偶然因素，这也就不足为怪了。对应于温度上升华氏1°所做的功，测量得到的最低值是587英尺磅，最高值是1,026英尺磅。 [英文](#)

当时焦耳先生指出，在他的研究中有一个著名的结论，即蒸汽机的热能转化为有效能量的效率非常低。著名的尤利乌斯·罗伯特·迈尔后来在德国也研究了这个问题，并独立地得到了同样的结论，但是他的观点还需要在未来的实验中去确证。焦耳先生在他的研究报告中还指出，他发现水流过细管子时会放出热量，通过实验他得到的数值是770英尺磅，这个值非常接近于今天我们承认的数值。另一份关于动物热量起源和转化的报告突出地表明了焦耳先生敏锐的洞察力和他在那个年代对规律的掌控能力。一位朋友曾经向他提到过哈勒尔的假说，该假说认为动物的热量可能起源于血液在静脉和动脉中流动时的摩擦。“这是毫无疑问的，”焦耳在回信中写到，“热量就是由这样的摩擦产生的，但是要知

道，在摩擦中消耗的机械力也是使静脉血与氧结合的亲和力引发的，所以动物系统的全部热量必然来自于化学反应。但动物在搬运东西或者上山的时候，我认为，动物将消耗其通过化学反应释放出的热量，而系统热量的减少与动物肌肉为完成这项工作所做的功成正比。”句子中突出强调的部分是焦耳在1843年的原稿中就标注了的。 [英文](#)

焦耳对于化学能与潜热的精确洞察力在这篇英国科学促进会论文的结束语中也有所体现。他写到，“我曾经竭力去证明两个原子结合时所释放的热量与化学反应产生的电流所释放的热量相等，也就是与使原子结合的化学力的强度成正比。现在，我要大胆地说得更明确一点，吸引力这个说法并不确切，应该说是两个原子在相互靠近时所克服的机械力，这个力决定了电流的强度，也决定了释放的热量。这样，我们就得到了一个简单的假说，可以用它来解释为什么在气体发生化合反应的过程中热量可以自由地释放，根据这个假说我们真的可以把‘潜热’看作是一种储备的机械力，就像上好的手表发条一样。例如，假设8磅氧和1磅氢在气态下混合在一起，然后发生了爆炸。爆炸所释放的热量差不多可以使60,000磅水的温度上升华氏1°，说明化合反应释放的机械能相当于把50,000,000磅的重物从地面提升1英尺所做的功。如果氧和氢可以在液态下发生反应，那么化合反应放出的热将小于气态的情况，因为原子之间的结合只需克服更小的距离。”这些陈述高屋建瓴地把握了分子物理学和热力学之间的关系，对此我无需再赘述了。 [英文](#)

焦耳先生极好地证实了他的实验所要建立的原理的重要性，但是他并没有满足于此，因为正如上面所提到的那样，实验结果还存在较大的差异。他于1844年采用全新的方法，精确地测量了空气在膨胀过程中的热量变化：首先，在抵抗外部压力的膨胀中，空气对外做功；其次，空气自由膨胀时，不对外做功。他用这种方式重新建立了热量消耗和做功之间的关系。他从5组不同的实验中推出了5个不同的热功当量；这些数据的吻合程度远远好于他以前的实验结果。测量得到的平均值是802英尺磅。1845年，焦耳用叶轮搅动水的实验测得的热功当量值是890英尺磅。1847年，他又用叶轮搅动水和鲸油，重复了上面的实验，测定了温度升高的度数，也就得到了致使温度升高的机械能的大小。一次实验得到的结果是781.5英尺磅，另一次实验的结果是782.1英尺磅。两者非常

接近，它们的平均值是781.8英尺磅。 英文

到目前为止，焦耳前10年的工作经验已经使他能够相当熟练地掌控与实验精度和成败密切相关的各种条件。1849年焦耳将他的成熟经验应用于热功当量的测定之中，做了40组水的摩擦实验，50组水银的摩擦实验和20组铸铁盘的摩擦实验。他从这些实验中推出了我们现在所使用的热功当量，即全世界都认可的“焦耳当量”。 英文

这些工作取得的成果非常重要也非常出名，每逢被人提及时总能得到高度评价。这就是焦耳先生的工作，它们构成了一个意义重大的定理的实验基础，不仅仅在实践层面上意义重大，对于科学哲学更是如此。自牛顿时代以来，还没有什么科学成果能比焦耳先生用实验所阐明的理论更重大。 英文

我没有提及焦耳先生科学著作中很多的小文章，也没有介绍他和威廉·汤姆孙爵士一同完成的重要研究。但是，我觉得我在这里介绍的内容已经足以说明：授予焦耳先生皇家学会的最高奖项，不仅仅是委员会给天才颁发的恰如其分的奖励，也是他在20年以前就应当得到的嘉奖。†

英文

将焦耳工作的简短历史和1871年科普利奖章获得者的相比，就可以从“环境”对两个具有相同资质的人的不同影响中得到启发。迈尔在放弃了机械设备的研究之后，经过深思熟虑颇有远见地选择了利用现有数据探索出一个计算热功当量的简便算法。而焦耳身处机械设备当中，致力于实验工作，为我们今天所接受的力学理论打下了广泛而坚实的基础。焦耳的大部分时间都花在了实验操作上；而迈尔则从繁琐的工作中解放出来，他有充足的时间将理论带入最深奥和最有价值的应用之中。如果将他们的位置交换一下，也许焦耳会成为迈尔，而迈尔则会成为焦耳。

英文

（王静 翻译；李军刚 审稿）

* 《哲学杂志》，1845年5月。

† 如果我及时地发现这一点，那么这段说明应该早于1871年科普利

奖。

Clerk Maxwell's Kinetic Theory of Gases

J. C. Maxwell

James Clerk Maxwell's recent kinetic theory of gases gave theoretical foundation to the macroscopic properties of gases. Here Maxwell defends his theory against a recent criticism. The theory predicts that a vertical column of gas should have the same temperature at all heights. However, the action of gravity implies that any molecule moving downward on some path should pick up energy, while those going upward should lose it. So shouldn't there be a net flow of energy downward? This argument, says Maxwell, assumes that particles projected upwards tend to have the same mean energy as those projected downward. Yet this cannot be so: at equilibrium, more must be ejected downwards, recovering the agreement with observations. [中文](#)

YOUR correspondent, Mr. Guthrie, has pointed out an, at first sight, very obvious and very serious objection to my kinetic theory of a vertical column of gas. According to that theory, a vertical column of gas acted on by gravity would be in thermal equilibrium if it were at a uniform temperature throughout, that is to say, if the mean energy of the molecules were the same at all heights. But if this were the case the molecules in their free paths would be gaining energy if descending, and losing energy if ascending. Hence, Mr. Guthrie argues, at any horizontal section of the column a descending molecule

would carry more energy down with it than an ascending molecule would bring up, and since as many molecules descend as ascend through the section, there would on the whole be a transfer of energy, that is, of heat, downwards; and this would be the case unless the energy were so distributed that a molecule in any part of its course finds itself, on an average, among molecules of the same energy as its own. An argument of the same kind, which occurred to me in 1866, nearly upset my belief in calculation, and it was some time before I discovered the weak point in it. [中文](#)

The argument assumes that, of the molecules which have encounters in a given stratum, those projected upwards have the same mean energy as those projected downwards. This, however, is not the case, for since the density is greater below than above, a greater *number* of molecules come from below than from above to strike those in the stratum, and therefore a greater number are projected from the stratum downwards than upwards. Hence since the total momentum of the molecules temporarily occupying the stratum remains zero (because, as a whole, it is at rest), the smaller number of molecules projected upwards must have a greater initial velocity than the larger number projected downwards. This much we may gather from general reasoning. It is not quite so easy, without calculation, to show that this difference between the molecules projected upwards and downwards from the same stratum exactly counteracts the tendency to a downward transmission of energy pointed out by Mr. Guthrie. The difficulty lies chiefly in forming exact expressions for the state of the molecules which instantaneously occupy a given stratum in terms of their state when projected from the various strata in which they had their last encounters. In my paper in the *Philosophical Transaction*, for 1867, on the “Dynamical Theory of Gases”, I have entirely avoided these difficulties by expressing everything in terms of what passes through the boundary of an element, and what exists or takes place inside it. By this method, which I have lately carefully verified and

considerably simplified, Mr. Guthrie's argument is passed by without ever becoming visible. It is well, however, that he has directed attention to it, and challenged the defenders of the kinetic theory to clear up their ideas of the result of those encounters which take place in a given stratum. [中文](#)

(8, 85; 1873)

克拉克·麦克斯韦的气体动力学理论

麦克斯韦

詹姆斯·克拉克·麦克斯韦最近提出的气体动力学理论为研究气体的宏观性质奠定了理论基础。在这篇文章中麦克斯韦坚持自己的理论，反驳了最近对其理论提出的批评。麦克斯韦的理论认为一个垂直气体柱在各个高度的温度应该保持一致。然而重力作用会使沿某一路径向向下运动的分子获得能量，使向上运动的粒子失去能量。所以似乎应该出现一个向下的净能流。麦克斯韦说，上述论点假设向上运动的粒子和向下运动的粒子平均能量相同。但这是不可能的：在准静态，向下运动的粒子更多，这样和观测结果就不会矛盾了。

[英文](#)

贵刊的通讯员格思里先生指出了我的垂直气体柱理论中一个初看上去非常明显而又严重的缺陷。根据那个理论，重力场中的一个垂直气体柱，如果各处温度相同，或者说如果处于不同高度的气体分子的平均动能相同，那么它将处于热平衡状态。但是如果事实确实如此，则自由运动的分子在向下运动的过程中动能将增加，向上运动的时候动能将减少。格思里先生论证说，如此一来，在气体柱的任何一个水平截面上，由于向上和向下运动的分子数目相同，向下运动的分子带走的动能将超过向上运动的分子带来的动能，所以整体上就会出现一个动能的转移，也就是热量的下移过程。要避免格思里所说的这个矛盾，只能假定动能沿高度的分布能够保证一个分子不管运动到哪里都与周边分子的动能相同。我在1866年也遇到了同样的问题，当时几乎动摇了我对计算结果的信心。一段时间之后我才发现这个观点中站不住脚的地方。

[英文](#)

上述观点假定：对于任一个给定水平层上发生碰撞的分子，向上运动的分子和向下运动的分子平均动能相同。这一点并不符合实际情况。

由于水平层下的分子密度大于水平层以上的，所以水平层下与水平层中分子发生碰撞的分子数目要大于水平层上与水平层中分子发生碰撞的分子数目，相应地，在水平层中发生碰撞而向下运动的分子数目也要大于发生碰撞而向上运动的分子数目。因此，既然该时刻水平层中的分子总动量保持为零（因为，从总体上来看水平层是静止的），那么相对于数目较大的向下运动的分子，数目较少的向上运动的分子就必须拥有更大的初始速度。从普通的推理中我们只能了解到这么多。不经过计算，想要说明从同一个水平层中向上和向下运动的分子在数目和速度上的差别正好能够抵消格思里先生指出的那个向下的动能转移趋势，是非常困难的。主要困难在于需要找到一个确切的表达式，将某一时刻各水平层中刚发生碰撞而运动到某一特定水平层上所有分子的状态描述出来。在我在1867年的《自然科学会报》上发表的一篇题为《论气体动力学》的文章中，我把一切都用穿过一个单元边界的通量和单元内部本来就存在或者生成的量来表达，这样就回避了上面提到的种种麻烦。不久前我曾仔细检验并大大地简化了这个方法，利用这个方法，格思里先生提出的问题被绕过去了，没有表现出来。但是，现在他将其提出来引起大家的注意是很有益处的，因为这对分子动力论的支持者是一个挑战，促使他们整理自己关于一个特定水平层上分子碰撞结果的构想。

[英文](#)

（何钧 翻译；鲍重光 审稿）

Molecules*

J. C. Maxwell

James Clerk Maxwell was sometimes accused of being a poor lecturer, but this talk delivered to the British Association offers a lucid, engaging picture of the current understanding of the molecular nature of matter. Maxwell made a decisive contribution himself with his kinetic theory of gases, which explained how the macroscopic properties of gases, such as the laws relating pressure, volume and temperature, could be explained from the microscopic motions of the constituent particles. Maxwell's estimate of the size of a hydrogen molecule is only slightly bigger than the modern view. And his discussion of molecular diffusion anticipates the work of Albert Einstein and Jean Perrin on Brownian motion that provided the first real evidence for molecules as physical entities. [中文](#)

AN atom is a body which cannot be cut in two. A molecule is the smallest possible portion of a particular substance. No one has ever seen or handled a single molecule. Molecular science, therefore, is one of those branches of study which deal with things invisible and imperceptible by our senses, and which cannot be subjected to direct experiment. [中文](#)

The mind of man has perplexed itself with many hard questions. Is space infinite, and if so in what sense? Is the material world infinite in extent, and are all places within that extent equally full of matter? Do

atoms exist, or is matter infinitely divisible? [中文](#)

The discussion of questions of this kind has been going on ever since men began to reason, and to each of us, as soon as we obtain the use of our faculties, the same old questions arise as fresh as ever. They form as essential a part of the science of the nineteenth century of our era, as of that of the fifth century before it. [中文](#)

We do not know much about the science organisation of Thrace twenty-two centuries ago, or of the machinery then employed for diffusing an interest in physical research. There were men, however, in those days, who devoted their lives to the pursuit of knowledge with an ardour worthy of the most distinguished members of the British Association; and the lectures in which Democritus explained the atomic theory to his fellow-citizens of Abdera realised, not in golden opinions only, but in golden talents, a sum hardly equalled even in America. [中文](#)

To another very eminent philosopher, Anaxagoras, best known in the world as the teacher of Socrates, we are indebted for the most important service to the atomic theory, which, after its statement by Democritus, remained to be done. Anaxagoras, in fact, stated a theory which so exactly contradicts the atomic theory of Democritus that the truth or falsehood of the one theory implies the falsehood or truth of the other. The question of the existence or non-existence of atoms cannot be presented to us this evening with greater clearness than in the alternative theories of these two philosophers. [中文](#)

Take any portion of matter, say a drop of water, and observe its properties. Like every other portion of matter we have ever seen, it is divisible. Divide it in two, each portion appears to retain all the properties of the original drop, and among others that of being divisible. The parts are similar to the whole in every aspect except in absolute size. [中文](#)

Now go on repeating the process of division till the separate portions of water are so small that we can no longer perceive or handle them. Still we have no doubt that the sub-division might be carried further, if our senses were more acute and our instruments more delicate. Thus far all are agreed, but now question arises, Can this sub-division be repeated for ever? [中文](#)

According to Democritus and the atomic school, we must answer in the negative. After a certain number of sub-divisions, the drop would be divided into a number of parts each of which is incapable of further sub-division. We should thus, in imagination, arrive at the atom, which, as its name literally signifies, cannot be cut in two. This is the atomic doctrine of Democritus, Epicurus, and Lucretius, and, I may add, of your lecturer. [中文](#)

According to Anaxagoras, on the other hand, the parts into which the drop is divided, are in all respects similar to the whole drop, the mere size of a body counting for nothing as regards the nature of its substance. Hence if the whole drop is divisible, so are its parts down to the minutest sub-divisions, and that without end. [中文](#)

The essence of the doctrine of Anaxagoras is that the parts of a body are in all respects similar to the whole. It was therefore called the doctrine of Homoiomereia. Anaxagoras did not of course assert this of the parts of organised bodies such as men and animals, but he maintained that those inorganic substances which appear to us homogeneous are really so, and that the universal experience of mankind testifies that every material body, without exception, is divisible. [中文](#)

The doctrine of atoms and that of homogeneity are thus in direct contradiction. [中文](#)

But we must now go on to molecules. Molecule is a modern word. It does not occur in *Johnson's Dictionary*. The ideas it embodies are those

belonging to modern chemistry. 中文

A drop of water, to return to our former example, may be divided into a certain number, and no more, of portions similar to each other. Each of these the modern chemist calls a molecule of water. But it is by no means an atom, for it contains two different substances, oxygen and hydrogen, and by a certain process the molecule may be actually divided into two parts, one consisting of oxygen and the other of hydrogen. According to the received doctrine, in each molecule of water there are two molecules of hydrogen and one of oxygen. Whether these are or are not ultimate atoms I shall not attempt to decide. 中文

We now see what a molecule is, as distinguished from an atom. 中文

A molecule of a substance is a small body such that if, on the one hand, a number of similar molecules were assembled together they would form a mass of that substance, while on the other hand, if any portion of this molecule were removed, it would no longer be able, along with an assemblage of other molecules similarly treated, to make up a mass of the original substance. 中文

Every substance, simple or compound, has its own molecule. If this molecule be divided, its parts are molecules of a different substance or substances from that of which the whole is a molecule. An atom, if there is such a thing, must be a molecule of an elementary substance. Since, therefore, every molecule is not an atom, but every atom is a molecule, I shall use the word molecule as the more general term.

中文

I have no intention of taking up your time by expounding the doctrines of modern chemistry with respect to the molecules of different substances. It is not the special but the universal interest of molecular science which encourages me to address you. It is not

because we happen to be chemists or physicists or specialists of any kind that we are attracted towards this centre of all material existence, but because we all belong to a race endowed with faculties which urge us on to search deep and ever deeper into the nature of things. 中

文

We find that now, as in the days of the earliest physical speculations, all physical researches appear to converge towards the same point, and every inquirer, as he looks forward into the dim region towards which the path of discovery is leading him, sees, each according to his sight, the vision of the same quest. 中文

One may see the atom as a material point, invested and surrounded by potential forces. Another sees no garment of force, but only the bare and utter hardness of mere impenetrability. 中文

But though many a speculator, as he has seen the vision recede before him into the innermost sanctuary of the inconceivably little, has had to confess that the quest was not for him, and though philosophers in every age have been exhorting each other to direct their minds to some more useful and attainable aim, each generation, from the earliest dawn of science to the present time, has contributed a due proportion of its ablest intellects to the quest of the ultimate atom.

中文

Our business this evening is to describe some researches in molecular science, and in particular to place before you any definite information which has been obtained respecting the molecules themselves. The old atomic theory, as described by Lucretius and revived in modern times, asserts that the molecules of all bodies are in motion, even when the body itself appears to be at rest. These motions of molecules are in the case of solid bodies confined within so narrow a range that even with our best microscopes we cannot detect that they alter their places at all. In liquids and gases, however, the molecules are not confined

within any definite limits, but work their way through the whole mass, even when that mass is not disturbed by any visible motion.

[中文](#)

This process of diffusion, as it is called, which goes on in gases and liquids and even in some solids, can be subjected to experiment, and forms one of the most convincing proofs of the motion of molecules.

[中文](#)

Now the recent progress of molecular science began with the study of the mechanical effect of the impact of these moving molecules when they strike against any solid body. Of course these flying molecules must beat against whatever is placed among them, and the constant succession of these strokes is, according to our theory, the sole cause of what is called the pressure of air and other gases. [中文](#)

This appears to have been first suspected by Daniel Bernoulli, but he had not the means which we now have of verifying the theory. The same theory was afterwards brought forward independently by Lesage, of Geneva, who, however, devoted most of his labour to the explanation of gravitation by the impact of atoms. Then Herapath, in his “Mathematical Physics”, published in 1847, made a much more extensive application of the theory to gases, and Dr. Joule, whose absence from our meeting we must all regret, calculated the actual velocity of the molecules of hydrogen. [中文](#)

The further development of the theory is generally supposed to have been begun with a paper by Krönig, which does not, however, so far as I can see, contain any improvement on what had gone before. It seems, however, to have drawn the attention of Prof. Clausius to the subject, and to him we owe a very large part of what has been since accomplished. [中文](#)

We all know that air or any other gas placed in a vessel presses against the sides of the vessel, and against the surface of any body

placed within it. On the kinetic theory this pressure is entirely due to the molecules striking against these surfaces, and thereby communicating to them a series of impulses which follow each other in such rapid succession that they produce an effect which cannot be distinguished from that of a continuous pressure. 中文

If the velocity of the molecules is given, and the number varied, then since each molecule, on an average, strikes the side of the vessel the same number of times, and with an impulse of the same magnitude, each will contribute an equal share to the whole pressure. The pressure in a vessel of given size is therefore proportional to the number of molecules in it, that is to the quantity of gas in it. 中文

This is the complete dynamical explanation of the fact discovered by Robert Boyle, that the pressure of air is proportional to its density. It shows also that of different portions of gas forced into a vessel, each produces its own part of the pressure independently of the rest, and this whether these portions be of the same gas or not. 中文

Let us next suppose that the velocity of the molecules is increased. Each molecule will now strike the sides of the vessel a greater number of times in a second, but besides this, the impulse of each blow will be increased in the same proportion, so that the part of the pressure due to each molecule will vary as the *square* of the velocity. Now the increase of the square of velocity corresponds, in our theory, to a rise of temperature, and in this way we can explain the effect of warming the gas, and also the law discovered by Charles that the proportional expansion of all gases between given temperatures is the same. 中文

The dynamical theory also tells us what will happen if molecules of different masses are allowed to knock about together. The greater masses will go slower than the smaller ones, so that, on an average, every molecule, great or small, will have the same energy of motion.

The proof of this dynamical theorem, in which I claim the priority, has recently been greatly developed and improved by Dr. Ludwig Boltzmann. The most important consequence which flows from it is that a cubic centimetre of every gas at standard temperature and pressure contains the same number of molecules. This is the dynamical explanation of Gay Lussac's law of the equivalent volumes of gases. But we must now descend to particulars, and calculate the actual velocity of a molecule of hydrogen. 中文

A cubic centimetre of hydrogen, at the temperature of melting ice and at a pressure of one atmosphere, weighs 0.00008954 grammes. We have to find at what rate this small mass must move (whether altogether or in separate molecules makes no difference) so as to produce the observed pressure on the sides of the cubic centimetre. This is the calculation which was first made by Dr. Joule, and the result is 1,859 metres per second. This is what we are accustomed to call a great velocity. It is greater than any velocity obtained in artillery practice. The velocity of other gases is less, as you will see by the table, but in all cases it is very great as compared with that of bullets. 中文

We have now to conceive the molecules of the air in this hall flying about in all directions, at a rate of about seventeen miles in a minute.

If all these molecules were flying in the same direction, they would constitute a wind blowing at the rate of seventeen miles a minute, and the only wind which approaches this velocity is that which proceeds from the mouth of a cannon. How, then, are you and I able to stand here? Only because the molecules happen to be flying in different directions, so that those which strike against our backs enable us to support the storm which is beating against our faces. Indeed, if this

molecular bombardment were to cease, even for an instant, our veins would swell, our breath would leave us, and we should, literally, expire. But it is not only against us or against the walls of the room that the molecules are striking. Consider the immense number of them, and the fact that they are flying in every possible direction, and you will see that they cannot avoid striking each other. Every time that two molecules come into collision, the paths of both are changed, and they go off in new directions. Thus each molecule is continually getting its course altered, so that in spite of its great velocity it may be a long time before it reaches any great distance from the point at which it set out. 中文

I have here a bottle containing ammonia. Ammonia is a gas which you can recognise by its smell. Its molecules have a velocity of six hundred metres per second, so that if their course had not been interrupted by striking against the molecules of air in the hall, everyone in the most distant gallery would have smelt ammonia before I was able to pronounce the name of the gas. But instead of this, each molecule of ammonia is so jostled about by the molecules of air, that it is sometimes going one way and sometimes another. It is like a hare which is always doubling, and though it goes a great pace, it makes very little progress. Nevertheless, the smell of ammonia is now beginning to be perceptible at some distance from the bottle. The gas does diffuse itself through the air, though the process is a slow one, and if we could close up every opening of this hall so as to make it airtight, and leave everything to itself for some weeks, the ammonia would become uniformly mixed through every part of the air in the hall. 中文

This property of gases, that they diffuse through each other, was first remarked by Priestley. Dalton showed that it takes place quite independently of any chemical action between the inter-diffusing gases. Graham, whose researches were especially directed towards

those phenomena which seem to throw light on molecular motions, made a careful study of diffusion, and obtained the first results from which the rate of diffusion can be calculated. [中文](#)

Still more recently the rates of diffusion of gases into each other have been measured with great precision by Prof. Loschmidt of Vienna.

[中文](#)

He placed the two gases in two similar vertical tubes, the lighter gas being placed above the heavier, so as to avoid the formation of currents. He then opened a sliding valve, so as to make the two tubes into one, and after leaving the gases to themselves for an hour or so, he shut the valve, and determined how much of each gas had diffused into the other. [中文](#)

As most gases are invisible, I shall exhibit gaseous diffusion to you by means of two gases, ammonia and hydrochloric acid, which, when they meet, form a solid product. The ammonia, being the lighter gas, is placed above the hydrochloric acid, with a stratum of air between, but you will soon see that the gases can diffuse through this stratum of air, and produce a cloud of white smoke when they meet. During the whole of this process no currents or any other visible motion can be detected. Every part of the vessel appears as calm as a jar of undisturbed air. [中文](#)

But, according to our theory, the same kind of motion is going on in calm air as in the inter-diffusing gases, the only difference being that we can trace the molecules from one place to another more easily when they are of a different nature from those through which they are diffusing. [中文](#)

If we wish to form a mental representation of what is going on among the molecules in calm air, we cannot do better than observe a swarm of bees, when every individual bee is flying furiously, first in one direction, and then in another, while the swarm, as a whole, either

remains at rest, or sails slowly through the air. 中文

In certain seasons, swarms of bees are apt to fly off to a great distance, and the owners, in order to identify their property when they find them on other people's ground, sometimes throw handfuls of flour at the swarm. Now let us suppose that the flour thrown at the flying swarm has whitened those bees only which happened to be in the lower half of the swarm, leaving those in the upper half free from flour. 中文

If the bees still go on flying hither and thither in an irregular manner, the floury bees will be found in continually increasing proportions in the upper part of the swarm, till they have become equally diffused through every part of it. But the reason of this diffusion is not because the bees were marked with flour, but because they are flying about. The only effect of the marking is to enable us to identify certain bees.

中文

We have no means of marking a select number of molecules of air, so as to trace them after they have become diffused among others, but we may communicate to them some property by which we may obtain evidence of their diffusion. 中文

For instance, if a horizontal stratum of air is moving horizontally, molecules diffusing out of this stratum into those above and below will carry their horizontal motion with them, and so tend to communicate motion to the neighbouring strata, while molecules diffusing out of the neighbouring strata into the moving one will tend to bring it to rest. The action between the strata is somewhat like that of two rough surfaces, one of which slides over the other, rubbing on it. Friction is the name given to this action between solid bodies; in the case of fluids it is called internal friction or viscosity. 中文

It is in fact only another kind of diffusion—a lateral diffusion of momentum, and its amount can be calculated from data derived from

observations of the first kind of diffusion, that of matter. The comparative values of the viscosity of different gases were determined by Graham in his researches on the transpiration of gases through long narrow tubes, and their absolute values have been deduced from experiments on the oscillation of discs by Oscar Meyer and myself.

中文

Another way of tracing the diffusion of molecules through calm air is to heat the upper stratum of the air in a vessel, and so observe the rate at which this heat is communicated to the lower strata. This, in fact, is a third kind of diffusion—that of energy, and the rate at which it must take place was calculated from data derived from experiments on viscosity before any direct experiments on the conduction of heat had been made. Prof. Stefan, of Vienna, has recently, by a very delicate method, succeeded in determining the conductivity of air, and he finds it, as he tells us, in striking agreement with the value predicted by the theory. 中文

All these three kinds of diffusion—the diffusion of matter, of momentum, and of energy—are carried on by the motion of the molecules. The greater the velocity of the molecules and the farther they travel before their paths are altered by collision with other molecules, the more rapid will be the diffusion. Now we know already the velocity of the molecules, and therefore by experiments on diffusion we can determine how far, on an average, a molecule travels without striking another. Prof. Clausius, of Bonn, who first gave us precise ideas about the motion of agitation of molecules, calls this distance the mean path of a molecule. I have calculated, from Prof. Loschmidt's diffusion experiments, the mean path of the molecules of four well-known gases. The average distance travelled by a molecule between one collision and another is given in the table. It is a very small distance, quite imperceptible to us even with our best microscopes. Roughly speaking, it is about the tenth part of the length

of a wave of light, which you know is a very small quantity. Of course the time spent on so short a path by such swift molecules must be very small. I have calculated the number of collisions which each must undergo in a second. They are given in the table and are reckoned by thousands of millions. No wonder that the travelling power of the swiftest molecule is but small, when its course is completely changed thousands of millions of times in a second. [中文](#)

The three kinds of diffusion also take place in liquids, but the relation between the rates at which they take place is not so simple as in the case of gases. The dynamical theory of liquids is not so well understood as that of gases, but the principal difference between a gas and a liquid seems to be that in a gas each molecule spends the greater part of its time in describing its free path, and is for a very small portion of its time engaged in encounters with other molecules, whereas in a liquid the molecule has hardly any free path, and is always in a state of close encounter with other molecules. [中文](#)

Hence in a liquid the diffusion of motion from one molecule to another takes place much more rapidly than the diffusion of the molecules themselves, for the same reason that it is more expeditious in a dense crowd to pass on a letter from hand to hand than to give it to a special messenger to work his way through the crowd. I have here a jar, the lower part of which contains a solution of copper sulphate, while the upper part contains pure water. It has been standing here since Friday, and you see how little progress the blue liquid has made in diffusing itself through the water above. The rate of diffusion of a solution of sugar has been carefully observed by Voit. Comparing his results with those of Loschmidt on gases, we find that about as much diffusion takes place in a second in gases as requires a day in liquids.

[中文](#)

The rate of diffusion of momentum is also slower in liquids than in gases, but by no means in the same proportion. The same amount of

motion takes about ten times as long to subside in water as in air, as you will see by what takes place when I stir these two jars, one containing water and the other air. There is still less difference between the rates at which a rise of temperature is propagated through a liquid and through a gas. [中文](#)

In solids the molecules are still in motion, but their motions are confined within very narrow limits. Hence the diffusion of matter does not take place in solid bodies, though that of motion and heat takes place very freely. Nevertheless, certain liquids can diffuse through colloid solids, such as jelly and gum, and hydrogen can make its way through iron and palladium. [中文](#)

We have no time to do more than mention that most wonderful molecular motion which is called electrolysis. Here is an electric current passing through acidulated water, and causing oxygen to appear at one electrode and hydrogen at the other. In the space between, the water is perfectly calm, and yet two opposite currents of oxygen and of hydrogen must be passing through it. The physical theory of this process has been studied by Clausius, who has given reasons for asserting that in ordinary water the molecules are not only moving, but every now and then striking each other with such violence that the oxygen and hydrogen of the molecules part company, and dance about through the crowd, seeking partners which have become dissociated in the same way. In ordinary water these exchanges produce, on the whole, no observable effect, but no sooner does the electromotive force begin to act than it exerts its guiding influence on the unattached molecules, and bends the course of each toward its proper electrode, till the moment when, meeting with an unappropriated molecule of the opposite kind, it enters again into a more or less permanent union with it till it is again dissociated by another shock. Electrolysis, therefore, is a kind of diffusion assisted by electromotive force. [中文](#)

Another branch of molecular science is that which relates to the exchange of molecules between a liquid and a gas. It includes the theory of evaporation and condensation, in which the gas in question is the vapour of the liquid, and also the theory of the absorption of a gas by a liquid of a different substance. The researches of Dr. Andrews on the relations between the liquid and the gaseous state have shown us that though the statements in our own elementary text-books may be so neatly expressed that they appear almost self-evident, their true interpretation may involve some principle so profound that, till the right man has laid hold of it, no one ever suspects that anything is left to be discovered. [中文](#)

These, then, are, some of the fields from which the data of molecular science are gathered. We may divide the ultimate results into three ranks, according to the completeness of our knowledge of them.

[中文](#)

To the first rank belong the relative masses of the molecules of different gases, and their velocities in metres per second. These data are obtained from experiments on the pressure and density of gases, and are known to a high degree of precision. [中文](#)

In the second rank we must place the relative size of the molecules of different gases, the length of their mean paths, and the number of collisions in a second. These quantities are deduced from experiments on the three kinds of diffusion. Their received values must be regarded as rough approximations till the methods of experimenting are greatly improved. [中文](#)

There is another set of quantities which we must place in the third rank, because our knowledge of them is neither precise, as in the first rank, nor approximate, as in the second, but is only as yet of the nature of a probable conjecture. These are the absolute mass of a molecule, its absolute diameter, and the number of molecules in a

cubic centimetre. We know the relative masses of different molecules with great accuracy, and we know their relative diameters approximately. From these we can deduce the relative densities of the molecules themselves. So far we are on firm ground. [中文](#)

The great resistance of liquids to compression makes it probable that their molecules must be at about the same distance from each other as that at which two molecules of the same substance in the gaseous form act on each other during an encounter. This conjecture has been put to the test by Lorenz Meyer, who has compared the densities of different liquids with the calculated relative densities of the molecules of their vapours, and has found a remarkable correspondence between them. [中文](#)

Now Loschmidt has deduced from the dynamical theory the following remarkable proportion:—As the volume of a gas is to the combined volume of all the molecules contained in it, so is the mean path of a molecule to one-eighth of the diameter of a molecule. [中文](#)

Assuming that the volume of the substance, when reduced to the liquid form, is not much greater than the combined volume of the molecules, we obtain from this proportion the diameter of a molecule. In this way Loschmidt, in 1865, made the first estimate of the diameter of a molecule. Independently of him and of each other, Mr. Stoney in 1868, and Sir W. Thomson in 1870, published results of a similar kind, those of Thomson being deduced not only in this way, but from considerations derived from the thickness of soap bubbles, and from the electric properties of metals. [中文](#)

According to the table, which I have calculated from Loschmidt's data, the size of the molecules of hydrogen is such that about two million of them in a row would occupy a millimetre, and a million million million million of them would weigh between four and five grammes.

[中文](#)

In a cubic centimetre of any gas at standard pressure and temperature there are about nineteen million million million molecules. All these numbers of the third rank are, I need not tell you, to be regarded as at present conjectural. In order to warrant us in putting any confidence in numbers obtained in this way, we should have to compare together a greater number of independent data than we have as yet obtained, and to show that they lead to consistent results. 中文

Thus far we have been considering molecular science as an inquiry into natural phenomena. But though the professed aim of all scientific work is to unravel the secrets of nature, it has another effect, not less valuable, on the mind of the worker. It leaves him in possession of methods which nothing but scientific work could have led him to invent, and it places him in a position from which many regions of nature, besides that which he has been studying, appear under a new aspect. 中文

The study of molecules has developed a method of its own, and it has also opened up new views of nature. 中文

When Lucretius wishes us to form a mental representation of the motion of atoms, he tells us to look at a sunbeam shining through a darkened room (the same instrument of research by which Dr. Tyndall makes visible to us the dust we breathe,) and to observe the motes which chase each other in all directions through it. This motion of the visible motes, he tells us, is but a result of the far more complicated motion of the invisible atoms which knock the motes about. In his dream of nature, as Tennyson tells us, he

“saw the flaring atom-streams
And torrents of her myriad universe,
Ruining along the illimitable inane,
Fly on to clash together again, and make
Another and another frame of things

For ever.”

And it is no wonder that he should have attempted to burst the bonds of Fate by making his atoms deviate from their courses at quite uncertain times and places, thus attributing to them a kind of irrational free will, which on his materialistic theory is the only explanation of that power of voluntary action of which we ourselves are conscious. [中文](#)

As long as we have to deal with only two molecules, and have all the data given us, we can calculate the result of their encounter, but when we have to deal with millions of molecules, each of which has millions of encounters in a second, the complexity of the problem seems to shut out all hope of a legitimate solution. [中文](#)

The modern atomists have therefore adopted a method which is I believe new in the department of mathematical physics, though it has long been in use in the Section of Statistics. When the working members of Section F get hold of a Report of the Census, or any other document containing the numerical data of Economic and Social Science, they begin by distributing the whole population into groups, according to age, income-tax, education, religious belief, or criminal convictions. The number of individuals is far too great to allow of their tracing the history of each separately, so that, in order to reduce their labour within human limits, they concentrate their attention on a small number of artificial groups. The varying number of individuals in each group, and not the varying state of each individual, is the primary datum from which they work. [中文](#)

This, of course, is not the only method of studying human nature. We may observe the conduct of individual men and compare it with that conduct which their previous character and their present circumstances, according to the best existing theory, would lead us to expect. Those who practise this method endeavour to improve their

knowledge of the elements of human nature, in much the same way as an astronomer corrects the elements of a planet by comparing its actual position with that deduced from the received elements. The study of human nature by parents and schoolmasters, by historians and statesmen, is therefore to be distinguished from that carried on by registrars and tabulators, and by those statesmen who put their faith in figures. The one may be called the historical, and the other the statistical method. [中文](#)

The equations of dynamics completely express the laws of the historical method as applied to matter, but the application of these equations implies a perfect knowledge of all the data. But the smallest portion of matter which we can subject to experiment consists of millions of molecules, not one of which ever becomes individually sensible to us. We cannot, therefore, ascertain the actual motion of any one of these molecules, so that we are obliged to abandon the strict historical method, and to adopt the statistical method of dealing with large groups of molecules. [中文](#)

The data of the statistical method as applied to molecular science are the sums of large numbers of molecular quantities. In studying the relations between quantities of this kind, we meet with a new kind of regularity, the regularity of averages, which we can depend upon quite sufficiently for all practical purposes, but which can make no claim to that character of absolute precision which belongs to the laws of abstract dynamics. [中文](#)

Thus molecular science teaches us that our experiments can never give us anything more than statistical information, and that no law deduced from them can pretend to absolute precision. But when we pass from the contemplation of our experiments to that of the molecules themselves, we leave the world of chance and change, and enter a region where everything is certain and immutable. [中文](#)

The molecules are conformed to a constant type with a precision which is not to be found in the sensible properties of the bodies which they constitute. In the first place the mass of each individual molecule, and all its other properties, are absolutely unalterable. In the second place the properties of all molecules of the same kind are absolutely identical. [中文](#)

Let us consider the properties of two kinds of molecules, those of oxygen and those of hydrogen. [中文](#)

We can procure specimens of oxygen from very different sources—from the air, from water, from rocks or every geological epoch. The history of these specimens has been very different, and if, during thousands of years, difference of circumstances could produce difference of properties, these specimens of oxygen would show it. [中文](#)

In like manner we may procure hydrogen from water, from coal, or, as Graham did, from meteoric iron. Take two litres of any specimen of hydrogen, it will combine with exactly one litre of any specimen of oxygen, and will form exactly two litres of the vapour of water. [中文](#)

Now if, during the whole previous history of either specimen, whether imprisoned in the rocks, flowing in the sea, or careering through unknown regions with the meteorites, any modification of the molecules had taken place, these relations would no longer be preserved. [中文](#)

But we have another and an entirely different method of comparing the properties of molecules. The molecule, though indestructible, is not a hard rigid body, but is capable of internal movements, and when these are excited it emits rays, the wavelength of which is a measure of the time of vibration of the molecule. [中文](#)

By means of the spectroscope the wavelengths of different kinds of light may be compared to within one ten-thousandth part. In this way it has been ascertained, not only that molecules taken from every specimen of hydrogen in our laboratories have the same set of periods of vibration, but that light, having the same set of periods of vibration, is emitted from the sun and from the fixed stars. [中文](#)

We are thus assured that molecules of the same nature as those of our hydrogen exist in those distant regions, or at least did exist when the light by which we see them was emitted. [中文](#)

From a comparison of the dimensions of the buildings of the Egyptians with those of the Greeks, it appears that they have a common measure. Hence, even if no ancient author had recorded the fact that the two nations employed the same cubit as a standard of length, we might prove it from the buildings themselves. We should also be justified in asserting that at some time or other a material standard of length must have been carried from one country to the other, or that both countries had obtained their standards from a common source.

[中文](#)

But in the heavens we discover by their light, and by their light alone, stars so distant from each other that no material thing can ever have passed from one to another, and yet this light, which is to us the sole evidence of the existence of these distant worlds, tells us also that each of them is built up of molecules of the same kinds as those which we find on earth. A molecule of hydrogen, for example, whether in Sirius or in Arcturus, executes its vibrations in precisely the same time. [中文](#)

Each molecule, therefore, throughout the universe, bears impressed on it the stamp of a metric system as distinctly as does the metre of the Archives at Paris, or the double royal cubit of the Temple of Karnac.

[中文](#)

No theory of evolution can be formed to account for the similarity of molecules, for evolution necessarily implies continuous change, and the molecule is incapable of growth or decay, of generation or destruction. [中文](#)

None of the processes of Nature, since the time when Nature began, have produced the slightest difference in the properties of any molecule. We are therefore unable to ascribe either the existence of the molecules or the identity of their properties to the operation of any of the causes which we call natural. [中文](#)

On the other hand, the exact quality of each molecule to all others of the same kind gives it, as Sir John Herschel has well said, the essential character of a manufactured article, and precludes the idea of its being eternal and self-existent. [中文](#)

Thus we have been led, along a strictly scientific path, very near to the point at which Science must stop. Not that Science is debarred from studying the internal mechanism of a molecule which she cannot take to pieces, any more than from investigating an organism which she cannot put together. But in tracing back the history of matter Science is arrested when she assures herself, on the one hand, that the molecule has been made, and on the other that it has not been made by any of the processes we call natural. [中文](#)

Science is incompetent to reason upon the creation of matter itself out of nothing. We have reached the utmost limit of our thinking faculties when we have admitted that because matter cannot be eternal and self-existent it must have been created. [中文](#)

It is only when we contemplate, not matter in itself, but the form in which it actually exists, that our mind finds something on which it can lay hold. [中文](#)

That matter, as such, should have certain fundamental properties—

that it should exist in space and be capable of motion, that its motion should be persistent, and so on, are truths which may, for anything we know, be of the kind which metaphysicians call necessary. We may use our knowledge of such truths for purposes of deduction but we have no data for speculating as to their origin. [中文](#)

But that there should be exactly so much matter and no more in every molecule of hydrogen is a fact of a very different order. We have here a particular distribution of matter—a *collocation*—to use the expression of Dr. Chalmers, of things which we have no difficulty in imagining to have been arranged otherwise. [中文](#)

The form and dimensions of the orbits of the planets, for instance, are not determined by any law of nature, but depend upon a particular collocation of matter. The same is the case with respect to the size of the earth, from which the standard of what is called the metrical system has been derived. But these astronomical and terrestrial magnitudes are far inferior in scientific importance to that most fundamental of all standards which forms the base of the molecular system. Natural causes, as we know, are at work, which tend to modify, if they do not at length destroy, all the arrangements and dimensions of the earth and the whole solar system. But though in the course of ages catastrophes have occurred and may yet occur in the heavens, though ancient systems may be dissolved and new systems evolved out of their ruins, the molecules out of which these systems are built—the foundation stones of the material universe—remain unbroken and unworn. [中文](#)

They continue this day as they were created, perfect in number and measure and weight, and from the ineffaceable characters impressed on them we may learn that those aspirations after accuracy in measurement, truth in statement, and justice in action, which we reckon among our noblest attributes as men, are ours because they are essential constituents of the image of Him Who in the beginning

created, not only the heaven and the earth, but the materials of which heaven and earth consist. 中文

Table of Moncular Date

		Hydrogen	Oxygen	Carbonic oxide	Carbonic acid
Rank I	Mass of molecule (hydrogen = 1)	1	16	14	22
	Velocity (of mean square), metres per second at 0°C	1859	465	497	396
Rank II	Mean path, tenth-metres.	965	560	482	379
	Collisions in a second, (millions)	17750	7646	9489	9720
Rank III	Diameter, tenth-metre	5.8	7.6	8.3	9.3
	Mass, twenty-fifth-grammes.	46	736	644	1012

中文

Table of Diffusion: $\frac{(\text{centimetre})^2}{\text{second}}$ measure

	Calculated	Observed	
H & O	0.7086	0.7214	Diffusion of matter observed by Loschmidt.
H & CO	0.6519	0.6422	
H & CO ₂	0.5575	0.5558	
O & CO	0.1807	0.1802	
O & CO ₂	0.1427	0.1409	
CO & CO ₂	0.1386	0.1406	
H	1.2990	1.49	Diffusion of momentum Graham and Meyer.
O	0.1884	0.213	
CO	0.1748	0.212	
CO ₂	0.1087	0.117	
Air		0.256	Diffusion of temperature observed by Stefan.
Copper		1.077	
Iron		0.183	
Cane sugar in water		0.00000365	Voit
Diffusion in a day		0.3144	
Salt in water		0.00000116	Fick

中文

(8, 437-441; 1873)

* Lecture delivered before the British Association at Bradford, by Prof. Clerk Maxwell, F. R. S.

分子*

麦克斯韦

有人认为詹姆斯·克拉克·麦克斯韦缺乏演讲天赋，但这篇在英国科学促进会所作的报告中，麦克斯韦对物质分子的那些得到普遍接受的性质描述得非常透彻，给人留下了深刻的印象。麦克斯韦在分子学方面作出了有决定意义的贡献，他提出的气体动力学理论能够说明如何用组成粒子的微观运动来解释气体的宏观性质，如与压力、体积和温度相关的定律。麦克斯韦对氢分子大小的估计只比现在的公认值略大一些。他对分子扩散现象的讨论促使阿尔伯特·爱因斯坦和让·佩兰开始了关于布朗运动的研究，这使人们第一次认识到分子是一种物理实体。 [英文](#)

原子是不能被一分为二的实体。分子是组成物质的最小单位。没有人看见或者摆弄过单个分子。因此，分子科学是研究不可见也不可感觉的事物的一门学问，我们无法对它进行直接实验。 [英文](#)

人类经常思索很多难以回答的问题。空间是无限的吗？如果是，是从什么意义上讲的？物质世界的范围是无限的吗？在这个范围内是不是每个地方都同等地充满了物质？原子存在吗？或物质是否无限可分？

[英文](#)

自从人类开始理性思考以来，关于这类问题的讨论就一直没有停止过。对于我们每个人来说，一旦开始用心智思考，那些古老的问题就会像从前一样令人觉得新奇。不论是在我们所处的19世纪，还是在公元前5世纪，这些问题都构成了科学的基本部分。 [英文](#)

我们对2,200年前位于色雷斯的科学组织所知甚少，也不知道他们用何种方式来传播对自然研究的兴趣。不过那时候确实有人毕生追求知

识，热情不亚于英国科学促进会中最杰出的成员。当德谟克利特向他的阿布德拉市民开设讲座讲解自己的原子理论时，他获得的高度评价和丰厚报酬即使在今天的美国也很少有人能比得上。 [英文](#)

另一位杰出的哲学家，即以身为苏格拉底的老师而闻名于世的阿那克萨哥拉在德谟克利特之后对原子学说作出了最重要的贡献。实际上，阿那克萨哥拉和德谟克利特两人的原子学说是如此地针锋相对，一方正确则另一方必错。今晚我们对原子到底是否存在这一问题的讨论，用这两位哲学家的对立理论来表达，是最清楚不过了。 [英文](#)

随便取一份物质，比如一滴水，来观察它的性质。就像我们看到的其他物质一样，它是可以分割的。把它分成两份，每一份都保持原来那滴水的所有性质，其他可以分割的物质也是一样。每一个部分除了尺寸比整体小些，其他各方面都和整体相似。 [英文](#)

就这么一直分下去，直到分出来的水滴小到我们再也看不见，也无法对它们进行操作。但是大家都明白，如果我们的感官更敏锐，我们的设备更精密，细分过程还是可以接着进行下去的。到此为止不会有什么异议，但是现在问题就来了：这样的细分过程可以永远继续下去吗？

[英文](#)

德谟克利特和原子学派的回答是否定的。经过一定次数的分割后，水滴就被分成很多很小的部分，每一部分都不能进一步细分了。也就是我们已经细分到了想象中的原子，原子这个名字的字面含义就是不可分的意思。这就是德谟克利特、伊壁鸠鲁、卢克莱修还有我，你们的演讲者，所赞成的原子论。 [英文](#)

另一方面，阿那克萨哥拉认为，水滴被分割成的各个部分，除了和物质性质无关的物体尺寸发生了变化以外，其他一切方面都和整个的水滴类似。因此，如果原来的水滴是可分的，那么分割得到的各个部分也应该是可分的，哪怕分到极小，永无止境。 [英文](#)

阿那克萨哥拉学说的根本点是：一个物体的部分和它的整体在所有方面都是相似的，所以被称为同质性学说。阿那克萨哥拉当然没有把它应用到人和动物这样的有机体的身上，但是他认为那些看上去是均质的

无机物的确是同质的，并且人类的普遍经验也能证实每一种物质实体毫无例外都是可分的。 [英文](#)

原子学说和同质性学说就是这样地针锋相对。 [英文](#)

但是现在我们必须转入对分子这个现代名词的讨论，它在《约翰逊词典》里是没有的。分子所包含的概念属于现代化学的范畴。 [英文](#)

回到我们原来的例子，一滴水能够最大限度地被分割成一定数量的彼此相似的部分。每一个这样的部分都是现代化学家称作的水分子。水分子包含两种不同的物质，氧和氢，所以它决不是一个原子。通过一定的处理方式，确实可以把水分子分解成两部分，一部分含氢，另一部分含氧。根据公认的理论，每一个水分子都包含两个氢分子和一个氧分子。至于这些氢分子和氧分子是不是不能再分解的原子，我这里先不去确定。 [英文](#)

现在我们明白了分子是什么，它和原子有什么不同。 [英文](#)

一种物质的分子是很小的，一方面，如果许多同样的分子聚合在一起，就会形成大量这种物质；另一方面，如果这些分子的某个部分缺失，它们与其他经过相同处理的分子聚合在一起也不能形成原来的物质。 [英文](#)

任何物质，无论是简单的还是复合的，都有自己的分子。如果这个分子再被分割，形成的部分就是其他物质的分子。一个原子，如果确实存在的话，应该是一种基本物质的分子。不是每个分子都是原子，但是每个原子都是分子，所以我将使用含义更广的分子这个术语。 [英文](#)

我不想浪费时间去详细解释现代化学关于各种物质分子的理论。我作这个报告的目的是讲述分子科学中普遍的而不是具体的问题。不是因为我们恰好是化学家、物理学家或者其他某个领域的专家才对这个与所有物质息息相关的中心问题感兴趣，而是因为我们都属于人类这个物种，其所具备的资质促使我们不断地深入研究事物的本质。 [英文](#)

现在我们发现，就像早期物理猜想时代一样，所有的物理研究似乎都汇集到了同一点上；每一个探求者，在眺望发现之途指向的茫茫区域

时，虽然目力各有不同，看到的却都是同一件宝物的幻像。 [英文](#)

有些人眼中的原子是一个物质点，被有势力场包围着。另一些人则看不到力的存在，只看到裸露而坚硬的不可穿透的实体。 [英文](#)

很多人看到幻像在眼前消退而去，躲进那不可思议的渺小之物最隐秘的庇护所之后，不得不承认宝物非他所属；各个时代的哲人们互相劝诫对方去追求更实际、更容易达到的目标。虽然如此，自从科学的启蒙时期直到今天，每一代都不乏最富才智的人投身于对最终原子的探求。

[英文](#)

我们今天晚上的任务是介绍分子科学中的一些研究成果，特别是向你们展示那些关于分子本身的现在已经比较确定的认识。卢克莱修所描述的旧原子论到了现代重获新生。他认为所有物体中的分子都在不停地运动，即便当物体本身处于静止状态时也不例外。在固体中，分子的运动只局限于一个很小的范围，哪怕是利用当前最好的显微镜我们也察觉不到它们的移动。但是对于液体和气体的情况，分子的运动没有受到确切的范围限制，可以在整个物质中移动，哪怕这个整体没有受到任何可见的运动的干扰。 [英文](#)

这个过程被称为扩散。它在气体、液体甚至一些固体中持续进行着，可以由实验验证，同时它也是分子运动论最有力的证明之一。

[英文](#)

现在分子科学的最新进展，是从研究这些运动着的分子碰撞固体表面的机械效应开始的。飞行中的分子一定会撞击所有置于其中的物质。根据我们的理论，这种持续不断的撞击，就是产生所谓的空气和其他气体压力的唯一原因。 [英文](#)

丹尼尔·伯努利可能是第一个想到这一点的人，但是他当时没有我们今天的实验手段来验证他的理论。后来日内瓦的勒萨热也独立提出过这个理论，但是他的工作主要是用原子碰撞来解释重力现象。赫拉帕斯在他1847年出版的《数学物理学》一书中，将这个理论更广泛地应用于各种气体。焦耳博士计算了氢分子的实际速度，今天他没有在场实在让人感到遗憾。 [英文](#)

大家普遍认为这一理论的进一步发展是从克勒尼希的一篇论文开始的。但在我个人看来，这篇文章本身并没有在前人工作的基础上作出什么改进。不过它引起了克劳修斯教授对这个问题的关注，而后者对以后的理论发展起了很大作用。 [英文](#)

我们都知道放置在一个容器中的空气或其他气体会对容器壁以及放置在其中的其他物体表面产生压力。根据气体动力学理论，这个压力完全是由分子碰撞这些表面产生的。这种碰撞带给表面的一系列冲击之间的间隔非常小，产生的效应和连续的压力没有什么两样。 [英文](#)

假定分子的速率一定，但数量不同。那么平均来说，每个分子碰撞器壁的次数相同，产生的冲击强度也相同，因此对总压力的贡献也相同。这样一来，一个固定容积的容器承受的压强和其中分子的总数量，也就是其中的气体总量，成正比。 [英文](#)

这就是罗伯特·玻意耳发现的空气压强正比于其密度这一事实的完整动力学解释。它还表明，如果我们将不同批次的气体加入容器，则无论它们的种类是否相同，每个部分都将独立地产生自己的分压强。 [英文](#)

下一步让我们假定分子速率增加的情形。因为每秒钟内，每个分子碰撞器壁的次数相应增加，同时每次碰撞的冲击强度也成比例增加，所以每个分子对压强的贡献和它的速度的平方成正比。在我们现在的理论中，分子速率平方的增加和温度的增加相对应。这样我们就能解释加热气体导致压强增加的效应，以及随温度增加各种气体体积同比增大的查理定律。 [英文](#)

动力论还告诉我们不同质量的气体分子互相碰撞会发生什么结果。质量大的分子比质量小的分子运动速率要小一些，所以平均来说，每个分子，不论质量大小，其动能都相同。 [英文](#)

对这一动力学定律的证明是我最先提出的，近来被路德维希·玻尔兹曼博士加以改进和发展。它的一个重要推论就是在标准温度和压强下，1立方厘米的任何气体都含有同等数量的分子，这就是盖·吕萨克定律关于相同体积气体的动力学解释。现在我们举一个具体的例子来计算一个

氢分子的实际速率。 [英文](#)

在温度为冰的熔点，压力为一个大气压时，1立方厘米氢气的质量是0.00008954克。这么小的质量的运动（是合在一起还是分散到各个分子，对结果没有影响）到底需要多大速率，才能在1立方厘米的容器壁上产生测量到的压强呢？焦耳博士首先对此进行了计算，他的结果是每秒1,859米。通常对我们来说，这是一个很大的速率，比任何炮弹的速率都要大。从附表中大家可以看到，其他气体的速率要小一些，但是无论如何都远大于子弹的速率。 [英文](#)

现在我们要设想一下这个大厅里的空气分子以每分钟17英里的速率向各个方向飞行。 [英文](#)

如果所有分子都向同一个方向飞行，它们就会形成速率为每分钟17英里的强风，只有从加农炮炮口出膛的风速能够接近这个速率。那么，你我怎么能够在这里保持站立？这只是因为这些分子飞行的方向各不相同，在前面和后面撞击我们的分子冲击作用互相抵消。事实上，如果这种分子碰撞哪怕停止一刻，我们也会静脉曲张，不能呼吸，一命呜呼。这些分子不只是撞击我们和房间四周的墙壁。考虑到它们数量巨大，正在四处乱飞，你会发现它们不可能不互相碰撞。每当两个分子撞到一起，其轨道就都会改变，而它们会飞向新的方向。这样每个分子都在不断地改变轨道，因而虽然其速率很快，但要从出发点移开一定距离也需要不少时间。 [英文](#)

我这里有一个里面装着氨气的瓶子。氨气的味道大家可以闻得出来。它的分子运动速率是每秒600米，因而如果它们的运动轨迹没有因为和大厅里的空气分子碰撞而改变，就算坐得最远的听众都会在我说出氨气这个名称之前闻到它。但是实际上并非如此，每个氨气分子都被空气分子撞来撞去，一会儿向东一会儿向西，就像一只野兔，老是改变方向，虽然步子很快，但是跑不了多远。虽然如此，在离瓶子一定距离以内的听众还是开始闻到氨气的味道了。氨气确实在空气中不断地扩散着，只是速率较慢而已，如果我们把大厅的所有出口都封起来，不让空气流走，并保持几个星期不动它，那么氨气就会均匀地散布在大厅的每个角落。 [英文](#)

气体的这个相互扩散的性质是由普里斯特利最先指出的。道尔顿指出这种扩散的发生与相互扩散的气体间发生的具体化学反应无关。格雷姆的研究工作集中在那些能为分子运动提供线索的现象上。他仔细研究了扩散现象，最早得到了可以用来计算扩散速率的结果。 [英文](#)

再晚些时候，维也纳的洛施密特教授精确地测量了气体分子相互扩散的速率。 [英文](#)

他把两种不同气体分别装入两个相似的竖直试管中，轻的气体放在重的气体上面以防止对流产生。随后打开滑动阀门让两个试管相通。将它们静置大约一个小时以后，他关上阀门，然后测量每种气体中有多少已经扩散到了另一种气体中。 [英文](#)

因为大多数气体都是不可见的，所以我得用氨气和盐酸这两种相遇后能生成固体反应物的气体来展示气体的扩散过程。氨气比较轻，所以放在盐酸上面，中间隔着一层空气。但是你们马上就可以看到，这两种气体能通过扩散穿过空气层而相遇，并产生一股白烟。整个过程看不到气体流动或者其他任何可见的运动。容器的每个部分都像一罐未受扰动的空气一样平静。 [英文](#)

但是根据我们的理论，这种气体间相互扩散的运动进程，同样在平静的空气中发生着。区别只是当扩散发生在不同气体间时，追踪分子从一处到另一处的移动要容易一些。 [英文](#)

如果我们想要在头脑中构思出一幅表现分子在平静空气中运动的图像，最好去观察一群蜜蜂，每只蜜蜂都拼命地飞来飞去，先朝一个方向飞，然后再朝另一个方向飞，但是整个蜂群不是停着不动，就是在空中缓慢地移动。 [英文](#)

有的季节蜂群可以飞得很远，养蜂人为了能在别人的地盘上也能认出自己的蜂群，有时会向蜂群洒一把面粉。现在我们假定面粉正好把蜂群下面一半的蜜蜂染白，而上面一半没有沾上面粉。 [英文](#)

如果这群蜜蜂继续散乱地飞来飞去，蜂群上半部就会有越来越多的沾上面粉的蜜蜂，直到它们均匀地分布于上下两部分。但是这种扩散的

原因不是因为蜜蜂沾上了面粉，而是因为它们到处乱飞。沾面粉标记的目的只是为了帮助我们识别特定的蜜蜂。 [英文](#)

我们没有办法标记一定数目的空气分子，使得它们在扩散到其他分子中之后还能被追踪到。但是我们可以用某些参数的传递来证明它们的扩散。 [英文](#)

比如说，如果一个水平空气层向水平方向移动，那么从该层扩散到上下两个相邻层的分子将携带水平动量，并把这个动量传递给相邻的上下空气层。而从相邻空气层中扩散进入这个水平移动的水平层的分子，会减慢水平层的移动。相邻水平层之间的作用，就像两个粗糙固体表面之间的滑动和摩擦。固体之间的这种作用叫做摩擦，在流体的情况下则称为内摩擦或者粘滞力。 [英文](#)

实际上这只不过是另一种类型的扩散——动量的横向扩散。其大小可以通过观察第一种扩散，也就是物质扩散的数据计算出来。研究气体通过长细管的流逸过程，格雷姆确定了不同气体的相对粘滞系数。粘滞系数的绝对值由奥斯卡·迈耶和我通过圆盘振动的实验结果推导得到。

[英文](#)

另一种跟踪分子在平静空气中扩散的方法是加热容器顶层的空气，然后观察热量向下层传递的速率。这实际上是第三种类型的扩散——能量扩散。在直接进行热传导的实验之前，这种传递的速率是由粘滞系数的实验结果计算出来的。维也纳的斯特藩教授最近通过一个极其精巧的方法，成功地确定了空气的传导系数，他发现测量值和理论预测值惊人地符合。 [英文](#)

所有这三种扩散——物质、动量和能量的扩散，都是由分子的运动完成的。分子的运动速率越大，在它与其他分子碰撞而使其运动方向发生改变之前所走的行程就越长，扩散的速率就越快。既然分子速率已知，通过扩散速率的实验，我们就可以确定一个分子在两次碰撞之间所走的平均距离。波恩的克劳修斯教授是第一个给出分子受激运动精确构想的人，他把这个距离叫做分子的平均自由程。根据洛施密特教授的扩散实验，我计算了4种常见气体的分子平均自由程。附表中列出了一个分子在两次碰撞之间的平均距离，这个距离非常之小，即使用最好的显

显微镜也不能分辨。它大概是光波长的 $1/10$ ，这样说你们就知道它有多小了。以分子的运动速率之大，行走这么短的距离，所用的时间当然是非常之短。我曾计算过一个分子每秒钟内碰撞的次数，结果也列在表中，都是几十亿次的水平。一秒钟之内方向要被改变几十亿次，难怪分子的运动速率虽大，却走不了多远。 [英文](#)

这三种扩散过程在液体中也会发生，但是它们之间的速率关系就不像在气体中那么简单。液体的动力学理论不像气体的理论那么完善。看上去它们之间的根本区别是：相对而言，气体分子大部分时间是自由飞行，和其他分子发生碰撞的时间不多；液体分子则正好相反，平均自由程很短，总是在和附近的分子发生密切接触。 [英文](#)

这样一来，液体中的动量扩散就比液体分子本身的扩散要快很多，这就好比在密集的人群中递送一封信，通过众人之手相传要比找一个专门的送信人穿越人群快一样。我这里有一个罐子，下半部装的是硫酸铜溶液，上半部装的是纯水。这个罐子从星期五就一直放在这里，而现在你们几乎看不出蓝色的硫酸铜扩散到上面的纯水中。沃伊特仔细计算了一种蔗糖溶液的扩散速率。把他的结果和洛施密特得到的气体扩散速率进行对比，我们发现在气体中一秒钟就能完成的扩散过程，在液体中则需要一整天。 [英文](#)

液体中动量的扩散速率也比气体中动量的扩散速率慢，但是没有差那么多。等量的运动在水中的衰减时间大概是空气中的10倍。让我来搅动一下这两个罐子，一个装的是水，另一个只有空气，大家看看结果是什么？液体和气体在温度传递上的速率差别还要更小一些。 [英文](#)

固体中的分子也在不停地运动，但是它们的运动被限制在很小的范围内。所以物质扩散不会发生在固体中，但动量和能量扩散可以非常自由地进行。不过某些液体可以渗过像果冻和树胶一类的胶质固体，而氢气能够透过铁和钯。 [英文](#)

时间有限，我们只能简单提一下电解这个最奇妙的分子运动现象。这里有电流通过酸性的水时，两个电极分别产生氧气和氢气。电极之间的水是完全静止的，但是其中必然有氢和氧的相对流动。克劳修斯研究了这一过程的物理学原理，给出理由认为普通水中的分子不但是运动

的，而且相互碰撞的力量还很大，造成水分子中氧和氢的分离，分离的氧和氢在水中四处游动，寻找因同样原因而游离的其他对象来结合。在普通水中，这个交换过程在整体上没有造成可观测的效应。但是一旦电动势开始起作用，就对独立分子的运动产生定向影响，驱使游离分子向相应的电极运动，直到碰上异性游离分子而形成相对稳定的结合体。这个结合体还有可能再次被冲击离解。这样来看，电解是一种电动势协助下的分子扩散过程。 [英文](#)

分子科学的另一个分支是关于液体和气体之间的分子交换。它既包括同一种物质气液两态之间的蒸发和凝结理论，也包括液体吸收不同种物质气体分子的理论。安德鲁斯博士关于气液两态之间关系的研究表明，虽然我们基本教科书中的结论看上去如此简洁，似乎是天经地义，但其实际的意义可能包含着非常深奥的原理。在有合适的人将其搞清楚之前，人们认为一切已经尽善尽美了。 [英文](#)

以上就是分子科学取得数据成果的一些领域。我们根据完整的相关知识，把这些最终的成果分成三个等级。 [英文](#)

第一个等级中有不同气体分子的相对质量以及它们以米每秒为单位的的速度。这些数据是根据气体压强和密度的实验结果得出的，精度很高。 [英文](#)

在第二个等级中，我们应该归入的是不同种气体分子的相对尺寸、平均自由程和每秒钟的碰撞次数。这些参数的量值是从三种扩散的实验结果推导出来的。在实验方法得到极大改进之前，这些公认的结果只能被看作是大概的近似。 [英文](#)

还有一批参数只能放进第三个等级，这是因为我们在这个等级中的相关知识只是基于可能的推测，既不像第一等级中的那么精确，也不像第二等级中的那样近似精确。这里面包括分子的绝对质量、绝对直径和1立方厘米中的分子数目。我们有不同分子的相对质量的准确结果，也大概知道它们的相对直径。由此我们可以得到分子的相对密度。这些都是确实有据的结果。 [英文](#)

液体强大的抗压缩性似乎表明：其分子之间的距离已经很近，和同

一物质的两个气态分子在碰撞时发生相互作用的距离差不多。洛伦茨·迈耶想了一个办法验证这个猜想，他对各种液体的密度和相应液体蒸气的相对密度的计算值进行比较，发现它们明显相关。 [英文](#)

现在洛施密特根据动力学原理推导出一个不寻常的比例关系：气体的体积和该气体中所有分子体积之和的比值，等于分子平均自由程与其直径的 $1/8$ 之比。 [英文](#)

假定气体液化后的体积，比相应分子的体积之和大不了多少，我们就可以通过这个比例关系得到分子的直径。1865年洛施密特由此第一次估计出了分子的直径。斯托尼先生在1868年，汤姆孙爵士于1870年也都各自独立发表了类似的结果。后者除了以上的考虑，还考虑了与肥皂泡厚度以及金属电特性有关的结果。 [英文](#)

表中的结果是我根据洛施密特的数据计算得到的。按照这个表，200万个氢分子排成一列，只有1毫米长。100万的四次方那么多的氢分子合起来的质量只有4~5克。 [英文](#)

在标准压强和温度下，1立方厘米的任何气体都含有 1.9×10^{19} 那么多的分子。这些量值都属于前面所说的第三个等级，不用我说你也知道，它们只是当前的推论。除非由独立方法得到的比现在多得多的数据经过比较后都趋向一致的结果，否则我们不能轻易接受以上的结果。

[英文](#)

到现在为止，我们一直认为分子科学是对自然现象的一种探索。虽然所有科学工作的目的都是为了揭示自然的秘密，但是它还有另外一个至少同样重要的作用，就是对科学工作者心灵的影响。只有科学工作才能让他们发明并掌握新的方法，这使他们站在了一个新的高度，看到除了自己的研究领域之外，其他许多自然领域也呈现出新的面貌。 [英文](#)

分子领域的研究发展了一套自己的方法，也打开了一扇观察自然的窗户。 [英文](#)

为了让我们在头脑中建立一幅原子运动的图像，卢克莱修让我们观

察一束射入暗室的日光（廷德尔博士用同样的设备展示了我们呼吸的灰尘的运动情况），在这束日光中我们可以看到向各个方向追逐乱窜的尘埃。他告诉我们，这些可见尘埃的运动，是更加复杂的不可见的原子运动不断将它们撞来撞去的结果。就像丁尼生告诉我们的一样，在卢克莱修梦想的自然中，他

“看见闪耀的原子流
和她在无穷宇宙中的激流，
在无尽的虚空中衰耗，
又飞来撞在一起，
创造一个又一个事物的构架，
永不止息。”

难怪他试图打破必然的枷锁，让他的原子在很不确定的时刻和地点改变轨迹，因而赋予它们一种非理性的自由意志，这就是他在物质理论中对我们所知的随机行为的产生所做的唯一解释。 [英文](#)

如果我们只需要研究两个分子，而且知道所有的数据，我们就可以计算它们相互碰撞的结果。但实际上有极多的分子，每个分子每秒钟都要经历极多的碰撞，问题的复杂性似乎超越了任何合理解答的可能性。

[英文](#)

现代原子论者采取了一种我认为在数学物理学科中是全新的方法，尽管它在统计部门中已经应用很久了。当F部门的工作人员得到一份人口普查报告，或者是其他包含经济和社会科学统计数据的文件时，他们先把整个人口按照年龄、所得税、教育水平、宗教信仰或犯罪记录分组。人口的数量太大，很难一一跟踪每个人的实际情况。为了在人力资源有限的情况下把工作量控制在合理范围，他们把注意力集中在少数几个人为划分出来的组群上，每个组群个体人数的变化，而非每个个体的状态变化是他们进行研究工作最初数据。 [英文](#)

这显然不是研究人类性质的唯一方法。我们可以观察个体的行为，也可以按照当前最好的理论，根据以往的特征预测目前情况下的行为，并把观察结果和预测的行为相比较。人们采用这种方法以增进他们对人类性质各个方面的认识，就像天文学家通过对比行星的实际位置和依据

已知参数预测的位置之间的差别来修正轨道参数一样。父母、校长、历史学家、政治家对人性的研究，和登记员、制表人还有注重数据的政治家的研究是不同的。一个可以叫历史方法，另一个则是统计方法。

英文

动力学方程完全是历史方法定律在物质研究上的应用，但应用这些方程需要知道所有的数据，然而哪怕是实验中物质最小的部分也包含着极多我们看不见的分子。我们不可能确定任何一个分子的实际运动状况，所以必须放弃严格的历史方法，采用统计方法来处理大量分子的情况。

英文

应用在分子科学中的统计方法牵涉的数据是大量分子的参量的总和。在研究这类参量之间的关系时，我们碰上了一种新的规律，也就是平均值的规律。对于实际应用，依赖这些规律就足够了，但是它们不能给出理论动力学定律所具有的绝对精确性。

英文

分子科学告诉我们：实验永远只能提供统计信息，从实验中总结的定律都没有绝对的精确性。但是当我们的关注点从实验转向分子本身时，我们就离开了充满偶然性和变化的世界，进入到一切都是确定不变的领域。

英文

分子都精确地具有恒定不变的属性，这种属性是分子所组成的物体的可测宏观参数所不具备的。首先，所有分子的质量和所有其他性质都是绝对不变的。其次，同种物质所有分子的所有性质都是绝对相同的。

英文

让我们来考虑一下氧和氢这两种分子的性质。

英文

我们可以从空气、水和各个地质时代的岩石等不同来源制备氧气样品。这些样品形成的历史完全不同。如果在几千年的时间里，不同的环境能造就不同的性质，这些氧气样品应该就能表现出这些不同的性质。

英文

同样地，我们可以从水、煤炭或者像格雷姆那样从陨铁中制备出氢气样品。任取两升氢气样品，它都可以和任取的一升氧气样品反应，正

好生成两升水蒸气。 [英文](#)

如果在任何一个样品的整个历史中，不论它是固锁在岩石中，还是漂流在海洋里，或者是跟着陨石穿越着未知的区域，只要分子发生了任何变化，上面的关系都不能再保持。 [英文](#)

我们有另一种完全不同的办法来比较分子的性质。分子虽然不能被毁灭，但也不是刚性实体，它有内部运动，当内部运动被激发时，分子发出射线，这个射线的波长表征了分子振动的周期。 [英文](#)

光谱仪可以比较不同光的波长差别，精度可达万分之一。用这个办法，我们可以确认，不但我们实验室中每一个氢气样品中的分子具有同样的振动周期组合，就连太阳和其他恒星发射的光也存在同样的振动周期组合。 [英文](#)

这样我们就确信了在茫茫的宇宙中也存在和我们的氢分子一样的分子，或者说至少在那些我们用来观察分子的光线放射出时，它们是存在的。 [英文](#)

比较古埃及和古希腊的建筑规模，可以感觉到它们似乎使用了同样的度量标准。因此，尽管历史上没有留下两个国家都使用同样的肘长作为长度标准的记载，我们也许可以通过建筑本身证明这一点。我们也有理由认为，肯定是某个实物长度标准在某个时候被人从一个国家带到了另一个国家，或者两个国家从同一个来源得到了这个标准。 [英文](#)

对天空中的星体，我们只是通过它们发射的光线证实它们的存在，它们之间的距离如此遥远，物质从一个恒星到另一个恒星的传递是完全不可能的，但是它们发射的光线，除了作为证明这些遥远天体存在的唯一证据以外，还告诉我们，组成每一个天体的分子都和我们在地球上发现的分子相同。比如，不论是天狼星还是大角星，上面的氢分子都以同样的周期振动。 [英文](#)

宇宙中的每一个分子，都铭刻着一个度量系统的痕迹，它的独特清晰，就如同巴黎档案局的米原尺，或者卡尔纳克神庙的皇家双肘尺一样。 [英文](#)

任何进化论都不能解释分子的相似性，因为进化隐含着不断的变化，而分子既 not 生长也不腐朽，不能被制造也不能被摧毁。 [英文](#)

自从自然界形成以来，自然界的所有过程都没能使任何分子的性质有丝毫的改变。所以我们不能把分子的存在或其性质的同一性归结为任何自然原因的作用。 [英文](#)

另一方面，正像约翰·赫歇尔爵士说的那样，同类分子精确相同的性质是其所构成的物质的根本特征，这就排除了分子的永恒自存在性。

[英文](#)

这样一来，我们就被引领着，沿着一条严格的科学道路，走到了科学的尽头。这不是说科学手段不能分解分子就不能用来研究分子的内部机制，就像不能因为科学不能组合成生物就不用她来研究生物一样。但在追溯物质的历史时，科学被困住了，她一方面确认分子已被创造，另一方面又确认任何自然界的进程都不能创造分子。 [英文](#)

科学不能理解物质如何被无中生有地创造出来。当我们承认由于物质不能永恒自存在，因此它一定已经被创造出来的时候，我们已经到了自己思维能力的极限。 [英文](#)

只有当我们思考物质的存在形式，而不是物质本身的时候，我们的思维才算找到了一些可以解决问题的线索。 [英文](#)

我们知道，形而上学者认为必要的真理是：物质必须具有一些基本的性质——它应该存在于空间中，能够运动，运动应该是持续的等等。我们可以利用已知的与这些真理有关的知识进行推导，但是并无数据可以用来猜测这些真理的本源。 [英文](#)

但是每一个氢分子的质量都正好是这么多，这个事实就完全是另一个性质了。这种质量的分布，或者用查默斯博士的词语——这种布置，实在是太特别了，让我们都不习惯。 [英文](#)

比如，行星轨道的形式和尺度，也不是由任何自然定律决定的，而是取决于特殊的质量的布置。作为米制计量体系标准的地球的尺寸也是这样。但是这些天文和地理的量值在科学上的重要性都远不能和构成成分

子系统基础的那些最基本的标准相比。我们知道自然界过程一直在起作用，就算最后不摧毁，它们至少也要改变地球和整个太阳系的秩序和尺寸。然而，尽管在历史上宇宙曾经发生过灾变，以后也可能再发生，虽然旧的体系可能被消灭，新的体系在旧体系的废墟上演化发展，但作为这些系统组成基础的分子——物质宇宙的基石，却不会被破坏和磨损。

英文

它们被创造的时候是什么样，现在还是什么样，数量、大小和质量都没有丝毫改变，从铭记在它们身上的不可磨灭的特征，我们也许能够明白，我们对测量的精准、言语的真切、行为的正义这些人类最高尚品质的追求，是因为它们也是造物主形象的根本组成部分。他当初不仅创造了天和地，也创造了组成天和地的所有物质。

英文

分子数据表

		氢	氧	一氧化碳	二氧化碳
第一等级	分子质量（氢=1）	1	16	14	22
	0℃下的速度（均方根），米 / 秒	1859	465	497	396
第二等级	平均自由程，10 ⁻¹⁰ 米	965	560	482	379
	每秒碰撞次数（百万次）	17750	7646	9489	9720
第三等级	直径，10 ⁻¹⁰ 米	5.8	7.6	8.3	9.3
	质量，10 ⁻²⁵ 克	46	736	644	1012

英文

(厘米)²

扩散数据表：单位是 秒

	计算值	测量值	
氢 & 氧	0.7086	0.7214	洛施密特观察的物质扩散
氢 & 一氧化碳	0.6519	0.6422	
氢 & 二氧化碳	0.5575	0.5558	
氧 & 一氧化碳	0.1807	0.1802	
氧 & 二氧化碳	0.1427	0.1409	
一氧化碳 & 二氧化碳	0.1386	0.1406	
氢	1.2990	1.49	格雷姆和迈耶的动量扩散
氧	0.1884	0.213	
一氧化碳	0.1748	0.212	
二氧化碳	0.1087	0.117	
空气		0.256	斯特藩观察的温度扩散
铜		1.077	
铁		0.183	
蔗糖在水溶液中		0.00000365	沃伊特
一天后扩散的距离		0.3144	
食盐在水溶液中		0.00000116	菲克

英文

* 皇家学会会员克拉克·麦克斯韦教授在布拉德福德对英国科学促进会作的报告。

On the Dynamical Evidence of the Molecular Constitution of Bodies*

J. C. Maxwell

Here James Clerk Maxwell offers an update on efforts to understand the properties of gases and liquids from first principles—what today is called statistical mechanics. Maxwell had made a decisive contribution with his kinetic theory of gases. Here he reports on other work, such as that of Rudolph Clausius, who introduced a theoretical quantity known as the “virial”, representing an average over all particle pairs of the product of the distance between the particles and the force of attraction or repulsion. Maxwell also mentions the work of two other figures, an unknown graduate student named Johannes Diderik van der Waals and an American physicist, Josiah Willard Gibbs. Both later became leaders in understanding the fundamental behavior of material systems. [中文](#)

I

WHEN any phenomenon can be described as an example of some general principle which is applicable to other phenomena, that phenomenon is said to be explained. Explanations, however, are of very various orders, according to the degree of generality of the principle which is made use of. Thus the person who first observed the

effect of throwing water into a fire would feel a certain amount of mental satisfaction when he found that the results were always similar, and that they did not depend on any temporary and capricious antipathy between the water and the fire. This is an explanation of the lowest order, in which the class to which the phenomenon is referred consists of other phenomena which can only be distinguished from it by the place and time of their occurrence, and the principle involved is the very general one that place and time are not among the conditions which determine natural processes. On the other hand, when a physical phenomenon can be completely described as a change in the configuration and motion of a material system, the dynamical explanation of that phenomenon is said to be complete. We cannot conceive any further explanation to be either necessary, desirable, or possible, for as soon as we know what is meant by the words configuration, motion, mass, and force, we see that the ideas which they represent are so elementary that they cannot be explained by means of anything else. [中文](#)

The phenomena studied by chemists are, for the most part, such as have not received a complete dynamical explanation. [中文](#)

Many diagrams and models of compound molecules have been constructed. These are the records of the efforts of chemists to imagine configurations of material systems by the geometrical relations of which chemical phenomena may be illustrated or explained. No chemist, however, professes to see in these diagrams anything more than symbolic representations of the various degrees of closeness with which the different components of the molecule are bound together.

[中文](#)

In astronomy, on the other hand, the configurations and motions of the heavenly bodies are on such a scale that we can ascertain them by direct observation. Newton proved that the observed motions indicate a continual tendency of all bodies to approach each other, and the

doctrine of universal gravitation which he established not only explains the observed motions of our system, but enables us to calculate the motions of a system in which the astronomical elements may have any values whatever. [中文](#)

When we pass from astronomical to electrical science, we can still observe the configuration and motion of electrified bodies, and thence, following the strict Newtonian path, deduce the forces with which they act on each other; but these forces are found to depend on the distribution of what we call electricity. To form what Gauss called a “*construirbar Vorstellung*” of the invisible process of electric action is the great desideratum in this part of science. [中文](#)

In attempting the extension of dynamical methods to the explanation of chemical phenomena, we have to form an idea of the configuration and motion of a number of material systems, each of which is so small that it cannot be directly observed. We have, in fact, to determine, from the observed external actions of an unseen piece of machinery, its internal construction. [中文](#)

The method which has been for the most part employed in conducting such inquiries is that of forming an hypothesis, and calculating what would happen if the hypothesis were true. If these results agree with the actual phenomena, the hypothesis is said to be verified, so long, at least, as some one else does not invent another hypothesis which agrees still better with the phenomena. [中文](#)

The reason why so many of our physical theories have been built up by the method of hypothesis is that the speculators have not been provided with methods and terms sufficiently general to express the results of their induction in its early stages. They were thus compelled either to leave their ideas vague and therefore useless, or to present them in a form the details of which could be supplied only by the illegitimate use of the imagination. [中文](#)

In the meantime the mathematicians, guided by that instinct which teaches them to store up for others the irrepressible secretions of their own minds, had developed with the utmost generality the dynamical theory of a material system. 中文

Of all hypotheses as to the constitution of bodies, that is surely the most warrantable which assumes no more than that they are material systems, and proposes to deduce from the observed phenomena just as much information about the conditions and connections of the material system as these phenomena can legitimately furnish. 中文

When examples of this method of physical speculation have been properly set forth and explained, we shall hear fewer complaints of the looseness of the reasoning of men of science, and the method of inductive philosophy will no longer be derided as mere guess-work. 中文

It is only a small part of the theory of the constitution of bodies which has as yet been reduced to the form of accurate deductions from known facts. To conduct the operations of science in a perfectly legitimate manner, by means of methodised experiment and strict demonstration, requires a strategic skill which we must not look for, even among those to whom science is most indebted for original observations and fertile suggestions. It does not detract from the merit of the pioneers of science that their advances, being made on unknown ground, are often cut off, for a time, from that system of communications with an established base of operations, which is the only security for any permanent extension of science. 中文

In studying the constitution of bodies we are forced from the very beginning to deal with particles which we cannot observe. For whatever may be our ultimate conclusions as to molecules and atoms, we have experimental proof that bodies may be divided into parts so small that we cannot perceive them. 中文

Hence, if we are careful to remember that the word particle means a small part of a body, and that it does not involve any hypothesis as to the ultimate divisibility of matter, we may consider a body as made up of particles, and we may also assert that in bodies or parts of bodies of measurable dimensions, the number of particles is very great indeed.

中文

The next thing required is a dynamical method of studying a material system consisting of an immense number of particles, by forming an idea of their configuration and motion, and of the forces acting on the particles, and deducing from the dynamical theory those phenomena which, though depending on the configuration and motion of the invisible particles, are capable of being observed in visible portions of the system. 中文

The dynamical principles necessary for this study were developed by the fathers of dynamics, from Galileo and Newton to Lagrange and Laplace; but the special adaptation of these principles to molecular studies has been to a great extent the work of Prof. Clausius of Bonn, who has recently laid us under still deeper obligations by giving us, in addition to the results of his elaborate calculations, a new dynamical idea, by the aid of which I hope we shall be able to establish several important conclusions without much symbolical calculation. 中文

The equation of Clausius, to which I must now call your attention, is of the following form:—

$$pV = \frac{2}{3} T - \frac{2}{3} \Sigma \Sigma \left(\frac{1}{2} Rr \right)$$

Here p denotes the pressure of a fluid, and V the volume of the vessel which contains it. The product pV , in the case of gases at constant temperature, remains, as Boyle's Law tells us, nearly constant for different volumes and pressures. This member of the equation, therefore, is the product of two quantities, each of which can be

directly measured. 中文

The other member of the equation consists of two terms, the first depending on the motion of the particles, and the second on the forces with which they act on each other. 中文

The quantity T is the kinetic energy of the system, or, in other words, that part of the energy which is due to the motion of the parts of the system. 中文

The kinetic energy of a particle is half the product of its mass into the square of its velocity, and the kinetic energy of the system is the sum of the kinetic energy of its parts. 中文

In the second term, r is the distance between any two particles, and R is the attraction between them. (If the force is a repulsion or a pressure, R is to be reckoned negative.) 中文

The quantity $\frac{1}{2}Rr$, or half the product of the attraction into the distance across which the attraction is exerted, is defined by Clausius as the virial of the attraction. (In the case of pressure or repulsion, the virial is negative.) 中文

The importance of this quantity was first pointed out by Clausius, who, by giving it a name, has greatly facilitated the application of his method to physical exposition. 中文

The virial of the system is the sum of the virials belonging to every pair of particles which exist in the system. This is expressed by the double sum $\Sigma\Sigma(\frac{1}{2}Rr)$, which indicates that the value of $\frac{1}{2}Rr$ is to be found for every pair of particles, and the results added together.

中文

Clausius has established this equation by a very simple mathematical process, with which I need not trouble you, as we are not studying mathematics tonight. We may see, however, that it indicates two

causes which may affect the pressure of the fluid on the vessel which contains it: the motion of its particles, which tends to increase the pressure, and the attraction of its particles, which tends to diminish the pressure. [中文](#)

We may therefore attribute the pressure of a fluid either to the motion of its particles or to a repulsion between them. [中文](#)

Let us test by means of this result of Clausius the theory that the pressure of a gas arises entirely from the repulsion which one particle exerts on another, these particles, in the case of gas in a fixed vessel, being really at rest. [中文](#)

In this case the virial must be negative, and since by Boyle's Law the product of pressure and volume is constant, the virial also must be constant, whatever the volume, in the same quantity of gas at constant temperature. It follows from this that Rr , the product of the repulsion of two particles into the distance between them, must be constant, or in other words that the repulsion must be inversely as the distance, a law which Newton has shown to be inadmissible in the case of molecular forces, as it would make the action of the distant parts of bodies greater than that of contiguous parts. In fact, we have only to observe that if Rr is constant, the virial of every pair of particles must be the same, so that the virial of the system must be proportional to the number of pairs of particles in the system—that is, to the square of the number of particles, or in other words to the square of the quantity of gas in the vessel. The pressure, according to this law, would not be the same in different vessels of gas at the same density, but would be greater in a large vessel than in a small one, and greater in the open air than in any ordinary vessel. [中文](#)

The pressure of a gas cannot therefore be explained by assuming repulsive forces between the particles. [中文](#)

It must therefore depend, in whole or in part, on the motion of the

particles. [中文](#)

If we suppose the particles not to act on each other at all, there will be no virial, and the equation will be reduced to the form

$$Vp = \frac{2}{3} T$$

If M is the mass of the whole quantity of gas, and c is the mean square of the velocity of a particle, we may write the equation—

$$Vp = \frac{1}{3} Mc^2,$$

or in words, the product of the volume and the pressure is one-third of the mass multiplied by the mean square of the velocity. If we now assume, what we shall afterwards prove by an independent process, that the mean square of the velocity depends only on the temperature, this equation exactly represents Boyle's Law. [中文](#)

But we know that most ordinary gases deviate from Boyle's Law, especially at low temperatures and great densities. Let us see whether the hypothesis of forces between the particles, which we rejected when brought forward as the sole cause of gaseous pressure, may not be consistent with experiment when considered as the cause of this deviation from Boyle's Law. [中文](#)

When a gas is in an extremely rarefied condition, the number of particles within a given distance of any one particle will be proportional to the density of the gas. Hence the virial arising from the action of one particle on the rest will vary as the density, and the whole virial in unit of volume will vary as the square of the density.

[中文](#)

Calling the density ρ , and dividing the equation by V , we get—

$$p = \frac{1}{3} \rho c^2 - \frac{2}{3} A \rho^2,$$

where A is a quantity which is nearly constant for small densities.

中文

Now, the experiments of Regnault show that in most gases, as the density increases the pressure falls below the value calculated by Boyle's Law. Hence the virial must be positive; that is to say, the mutual action of the particles must be in the main attractive, and the effect of this action in diminishing the pressure must be at first very nearly as the square of the density. 中文

On the other hand, when the pressure is made still greater the substance at length reaches a state in which an enormous increase of pressure produces but a very small increase of density. This indicates that the virial is now negative, or, in other words, the action between the particles is now, in the main, repulsive. We may therefore conclude that the action between two particles at any sensible distance is quite insensible. As the particles approach each other the action first shows itself as an attraction, which reaches a maximum, then diminishes, and at length becomes a repulsion so great that no attainable force can reduce the distance of the particles to zero. 中

文

The relation between pressure and density arising from such an action between the particles is of this kind. 中文

As the density increases from zero, the pressure at first depends almost entirely on the motion of the particles, and therefore varies almost exactly as the pressure, according to Boyle's Law. As the density continues to increase, the effect of the mutual attraction of the particles becomes sensible, and this causes the rise of pressure to be less than that given by Boyle's Law. If the temperature is low, the effect of attraction may become so large in proportion to the effect of motion that the pressure, instead of always rising as the density increases, may reach a maximum, and then begin to diminish. 中

文

At length, however, as the average distance of the particles is still further diminished, the effect of repulsion will prevail over that of attraction, and the pressure will increase so as not only to be greater than that given by Boyle's Law, but so that an exceedingly small increase of density will produce an enormous increase of pressure.

中文

Hence the relation between pressure and volume may be represented by the curve $A B C D E F G$, where the horizontal ordinate represents the volume, and the vertical ordinate represents the pressure. 中文

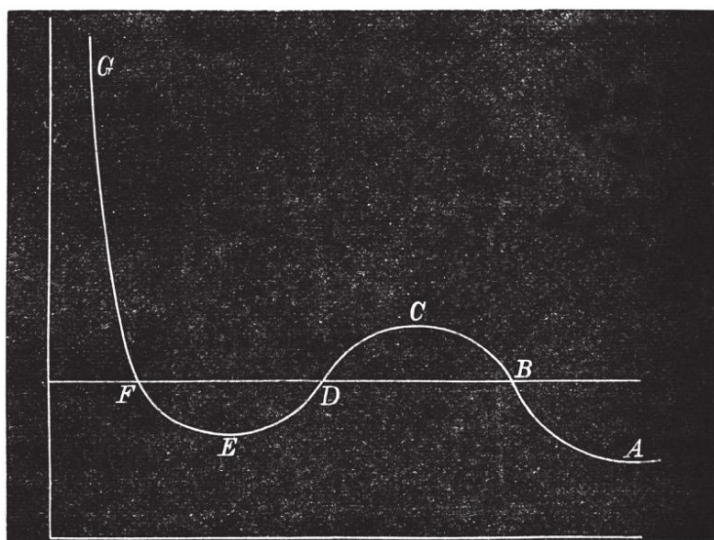


Fig. 1 中文

As the volume diminishes, the pressure increases up to the point C , then diminishes to the point E , and finally increases without limit as the volume diminishes. 中文

We have hitherto supposed the experiment to be conducted in such a way that the density is the same in every part of the medium. This, however, is impossible in practice, as the only condition we can impose on the medium from without is that the whole of the medium

shall be contained within a certain vessel. Hence, if it is possible for the medium to arrange itself so that part has one density and part another, we cannot prevent it from doing so. 中文

Now the points B and F represent two states of the medium in which the pressure is the same but the density very different. The whole of the medium may pass from the state B to the state F , not through the intermediate states $C D E$, but by small successive portions passing directly from the state B to the state F . In this way the successive states of the medium as a whole will be represented by points on the straight line $B F$, the point B representing it when entirely in the rarefied state, and F representing it when entirely condensed. This is what takes place when a gas or vapour is liquefied. 中文

Under ordinary circumstances, therefore, the relation between pressure and volume at constant temperature is represented by the broken line $A B F G$. If, however, the medium when liquefied is carefully kept from contact with vapour, it may be preserved in the liquid condition and brought into states represented by the portion of the curve between F and E . It is also possible that methods may be devised whereby the vapour may be prevented from condensing, and brought into states represented by points in $B C$. 中文

The portion of the hypothetical curve from C to E represents states which are essentially unstable, and which cannot therefore be realised. 中文

Now let us suppose the medium to pass from B to F along the hypothetical curve $B C D E F$ in a state always homogeneous, and to return along the straight line $F B$ in the form of a mixture of liquid and vapour. Since the temperature has been constant throughout, no heat can have been transformed into work. Now the heat transformed into work is represented by the excess of the area $F D E$ over $B C D$. Hence the condition which determines the maximum pressure of the

vapour at given temperature is that the line $B F$ cuts off equal areas from the curve above and below. 中文

The higher the temperature, the greater the part of the pressure which depends on motion, as compared with that which depends on forces between the particles. Hence, as the temperature rises, the dip in the curve becomes less marked, and at a certain temperature the curve, instead of dipping, merely becomes horizontal at a certain point, and then slopes upward as before. This point is called the critical point. It has been determined for carbonic acid by the masterly researches of Andrews. It corresponds to a definite temperature, pressure and density. 中文

At higher temperatures the curve slopes upwards throughout, and there is nothing corresponding to liquefaction in passing from the rarest to the densest state. 中文

The molecular theory of the continuity of the liquid and gaseous states forms the subject of an exceedingly ingenious thesis by Mr. Johannes Diderik van der Waals†, a graduate of Leyden. There are certain points in which I think he has fallen into mathematical errors, and his final result is certainly not a complete expression for the interaction of real molecules, but his attack on this difficult question is so able and so brave, that it cannot fail to give a notable impulse to molecular science. It has certainly directed the attention of more than one inquirer to the study of the Low-Dutch language in which it is written.

中文

The purely thermodynamical relations of the different states of matter do not belong to our subject, as they are independent of particular theories about molecules. I must not, however, omit to mention a most important American contribution to this part of thermodynamics by Prof. Willard Gibbs‡, of Yale College, U. S., who has given us a remarkably simple and thoroughly satisfactory method of representing

the relations of the different states of matter by means of a model. By means of this model, problems which had long resisted the efforts of myself and others may be solved at once. [中文](#)

(11, 357-359; 1875)

II

Let us now return to the case of a highly rarefied gas in which the pressure is due entirely to the motion of its particles. It is easy to calculate the mean square of the velocity of the particles from the equation of Clausius, since the volume, the pressure, and the mass are all measurable quantities. Supposing the velocity of every particle the same, the velocity of a molecule of oxygen would be 461 metres per second, of nitrogen 492, and of hydrogen 1,844, at the temperature 0 °C. [中文](#)

The explanation of the pressure of a gas on the vessel which contains it by the impact of its particles on the surface of the vessel has been suggested at various times by various writers. The fact, however, that gases are not observed to disseminate themselves through the atmosphere with velocities at all approaching those just mentioned, remained unexplained, till Clausius, by a thorough study of the motions of an immense number of particles, developed the methods and ideas of modern molecular science. [中文](#)

To him we are indebted for the conception of the mean length of the path of a molecule of a gas between its successive encounters with other molecules. As soon as it was seen how each molecule, after describing an exceedingly short path, encounters another, and then describes a new path in a quite different direction, it became evident that the rate of diffusion of gases depends not merely on the velocity of the molecules, but on the distance they travel between each encounter. [中文](#)

I shall have more to say about the special contributions of Clausius to molecular science. The main fact, however, is, that he opened up a new field of mathematical physics by showing how to deal mathematically with moving systems of innumerable molecules.

中文

Clausius, in his earlier investigations at least, did not attempt to determine whether the velocities of all the molecules of the same gas are equal, or whether, if unequal, there is any law according to which they are distributed. He therefore, as a first hypothesis, seems to have assumed that the velocities are equal. But it is easy to see that if encounters take place among a great number of molecules, their velocities, even if originally equal, will become unequal, for, except under conditions which can be only rarely satisfied, two molecules having equal velocities before their encounter will acquire unequal velocities after the encounter. By distributing the molecules into groups according to their velocities, we may substitute for the impossible task of following every individual molecule through all its encounters, that of registering the increase or decrease of the number of molecules in the different groups. 中文

By following this method, which is the only one available either experimentally or mathematically, we pass from the methods of strict dynamics to those of statistics and probability. 中文

When an encounter takes place between two molecules, they are transferred from one pair of groups to another, but by the time that a great many encounters have taken place, the number which enter each group is, on an average, neither more nor less than the number which leave it during the same time. When the system has reached this state, the numbers in each group must be distributed according to some definite law. 中文

As soon as I became acquainted with the investigations of Clausius, I

endeavoured to ascertain this law.

中文

The result which I published in 1860 has since been subjected to a more strict investigation by Dr. Ludwig Boltzmann, who has also applied his method to the study of the motion of compound molecules. The mathematical investigation, though, like all parts of the science of probabilities and statistics, it is somewhat difficult, does not appear faulty. On the physical side, however, it leads to consequences, some of which, being manifestly true, seem to indicate that the hypotheses are well chosen, while others seem to be so irreconcilable with known experimental results, that we are compelled to admit that something essential to the complete statement of the physical theory of molecular encounters must have hitherto escaped us.

中文

I must now attempt to give you some account of the present state of these investigations, without, however, entering into their mathematical demonstration.

中文

I must begin by stating the general law of the distribution of velocity among molecules of the same kind.

中文

If we take a fixed point in this diagram and draw from this point a line representing in direction and magnitude the velocity of a molecule, and make a dot at the end of the line, the position of the dot will indicate the state of motion of the molecule.

中文

If we do the same for all the other molecules, the diagram will be dotted all over, the dots being more numerous in certain places than in others.

中文

The law of distribution of the dots may be shown to be the same as that which prevails among errors of observation or of adjustment.

中文

The dots in the diagram before you may be taken to represent the velocities of molecules, the different observations of the position of the same star, or the bullet-holes round the bull's eye of a target, all of which are distributed in the same manner. 中文

The velocities of the molecules have values ranging from zero to infinity, so that in speaking of the average velocity of the molecules we must define what we mean. 中文

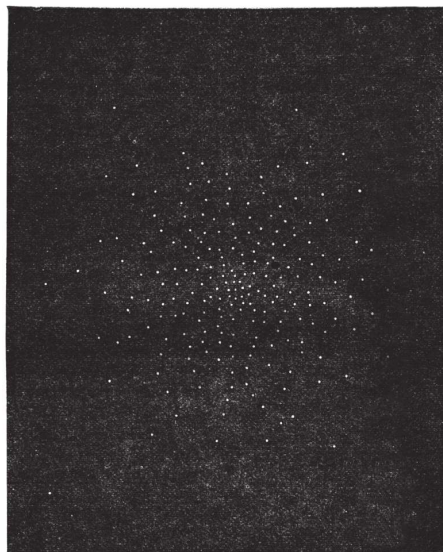


Fig. 2. Diagram of Velocities 中文

The most useful quantity for purposes of comparison and calculation is called the “velocity of mean square”. It is that velocity whose square is the average of the squares of the velocities of all the molecules.

中文

This is the velocity given above as calculated from the properties of different gases. A molecule moving with the velocity of mean square has a kinetic energy equal to the average kinetic energy of all the molecules in the medium, and if a single mass equal to that of the whole quantity of gas were moving with this velocity, it would have the same kinetic energy as the gas actually has, only it would be in a visible form and directly available for doing work. 中文

If in the same vessel there are different kinds of molecules, some of greater mass than others, it appears from this investigation that their velocities will be so distributed that the average kinetic energy of a molecule will be the same, whether its mass be great or small. 中

文

Here we have perhaps the most important application which has yet been made of dynamical methods to chemical science. For, suppose that we have two gases in the same vessel. The ultimate distribution of agitation among the molecules is such that the average kinetic energy of an individual molecule is the same in either gas. This ultimate state is also, as we know, a state of equal temperature. Hence the condition that two gases shall have the same temperature is that the average kinetic energy of a single molecule shall be the same in the two gases.

中文

Now, we have already shown that the pressure of a gas is two-thirds of the kinetic energy in unit of volume. Hence, if the pressure as well as the temperature be the same in the two gases, the kinetic energy per unit of volume is the same, as well as the kinetic energy molecule. There must, therefore, be the same number of molecules in unit of volume in the two gases. 中文

This result coincides with the law of equivalent volumes established by Gay Lussac. This law, however, has hitherto tested on purely chemical evidence, the relative masses of the molecules of different substances having been deduced from the proportions in which the substances enter into chemical combination. It is now demonstrated on dynamical principles. The molecule is defined as that small portion of the substance which moves as one lump during the motion of agitation. This is a purely dynamical definition, independent of any experiments on combination. 中文

The density of a gaseous medium, at standard temperature and

pressure, is proportional to the mass of one of its molecules as thus defined. [中文](#)

We have thus a safe method of estimating the relative masses of molecules of different substances when in the gaseous state. This method is more to be depended on than those founded on electrolysis or on specific heat, because our knowledge of the conditions of the motion of agitation is more complete than our knowledge of electrolysis, or of the internal motions of the constituents of a molecule. [中文](#)

I must now say something about these internal motions, because the greatest difficulty which the kinetic theory of gases has yet encountered belongs to this part of the subject. [中文](#)

We have hitherto considered only the motion of the centre of mass of the molecule. We have now to consider the motion of the constituents of the molecule relative to the centre of mass. [中文](#)

If we suppose that the constituents of a molecule are atoms, and that each atom is what is called a material point, then each atom may move in three different and independent ways, corresponding to the three dimensions of space, so that the number of variables required to determine the position and configuration of all the atoms of the molecule is three times the number of atoms. [中文](#)

It is not essential, however, to the mathematical investigation to assume that the molecule is made up of atoms. All that is assumed is that the position and configuration of the molecule can be completely expressed by a certain number of variables. [中文](#)

Let us call this number n . [中文](#)

Of these variables, three are required to determine the position of the centre of mass of the molecule, and the remaining $n-3$ to determine its

configuration relative to its centre of mass. 中文

To each of the n variables corresponds a different kind of motion.

中文

The motion of translation of the centre of mass has three components.

中文

The motions of the parts relative to the centre of mass have $n-3$ components. 中文

The kinetic energy of the molecule may be regarded as made up of two parts—that of the mass of the molecule supposed to be concentrated at its centre of mass, and that of the motions of the parts relative to the centre of mass. The first part is called the energy of translation, the second that of rotation and vibration. The sum of these is the whole energy of motion of the molecule. 中文

The pressure of the gas depends, as we have seen, on the energy of translation alone. The specific heat depends on the rate at which the whole energy, kinetic and potential, increases as the temperature rises. 中文

Clausius had long ago pointed out that the ratio of increment of the whole energy to that of the energy of translation may be determined if we know by experiment the ratio of the specific heat at constant pressure to that at constant volume. 中文

He did not, however, attempt to determine *à priori* the ratio of the two parts of the energy, though he suggested, as an extremely probable hypothesis, that the average values of the two parts of the energy in a given substance always adjust themselves to the same ratio. He left the numerical value of this ratio to be determined by experiment.

中文

In 1860 I investigated the ratio of the two parts of the energy on the

hypothesis that the molecules are elastic bodies of invariable form. I found, to my great surprise, that whatever be the shape of the molecules, provided they are not perfectly smooth and spherical, the ratio of the two parts of the energy must be always the same, the two parts being in fact equal. 中文

This result is confirmed by the researches of Boltzmann, who has worked out the general case of a molecule having n variables. 中文

He finds that while the average energy of translation is the same for molecules of all kinds at the same temperature, the whole energy of motion is to the energy of translation as n to 3. 中文

For a rigid body $n=6$, which makes the whole energy of motion twice the energy of energy of translation. 中文

But if the molecule is capable of changing its form under the action of impressed forces, it must be capable of storing up potential energy, and if the forces are such as to ensure the stability of the molecule, the average potential energy will increase when the average energy of internal motion increases. 中文

Hence, as the temperature rises, the increments of the energy of translation, the energy of internal motion, and the potential energy are as 3, $(n-3)$, and e respectively, where e is a positive quantity of unknown value depending on the law of the force which binds together the constituents of the molecule. 中文

When the volume of the substance is maintained constant, the effect of the application of heat is to increase the whole energy. We thus find for the specific heat of a gas at constant volume—

$$\frac{1}{2J} \frac{p_0 V_0}{273^\circ} (n + e)$$

where p_0 and V_0 are the pressure and volume of unit of mass at zero centigrade, or 273° absolute temperature, and J is the dynamical equivalent of heat. The specific heat at constant pressure is

$$\frac{1}{2J} \frac{p_0 V_0}{273^\circ} (n + 2 + e)$$

中文

In gases whose molecules have the same degree of complexity the value of n is the same, and that of e may be the same. 中文

If this is the case, the specific heat is inversely as the specific gravity, according to the law of Dulong and Petit, which is, to a certain degree of approximation, verified by experiment. 中文

But if we take the actual values of the specific heat as found by Regnault and compare them with this formula, we find that $n + e$ for air and several other gases cannot be more than 4.9. For carbonic acid and steam it is greater. We obtain the same result if we compare the ratio of the calculated specific heats

$$\frac{2 + n + e}{n + e}$$

with the ratio as determined by experiment for various gases, namely, 1.408. 中文

And here we are brought face to face with the greatest difficulty which the molecular theory has yet encountered, namely, the interpretation of the equation $n + e = 4.9$. 中文

If we suppose that the molecules are atoms—mere material points, incapable of rotatory energy or internal motion—then n is 3 and e is zero, and the ratio of the specific heats is 1.66, which is too great for any real gas. 中文

But we learn from the spectroscope that a molecule can execute vibrations of constant period. It cannot therefore be a mere material point, but a system capable of changing its form. Such a system cannot have less than six variables. This would make the greatest value of the ratio of the specific heats 1.33, which is too small for hydrogen, oxygen, nitrogen, carbonic oxide, nitrous oxide, and hydrochloric acid. 中文

But the spectroscope tells us that some molecules can execute a great many different kinds of vibrations. They must therefore be systems of a very considerable degree of complexity, having far more than six variables. Now, every additional variable introduces an additional amount of capacity for internal motion without affecting the external pressure. Every additional variable, therefore, increases the specific heat, whether reckoned at constant pressure or at constant volume.

中文

So does any capacity which the molecule may have for storing up energy in the potential form. But the calculated specific heat is already too great when we suppose the molecule to consist of two atoms only. Hence every additional degree of complexity which we attribute to the molecule can only increase the difficulty of reconciling the observed with the calculated value of the specific heat. 中文

I have now put before you what I consider to be the greatest difficulty yet encountered by the molecular theory. Boltzmann has suggested that we are to look for the explanation in the mutual action between the molecules and the etherial medium which surrounds them. I am afraid, however, that if we call in the help of this medium, we shall only increase the calculated specific heat, which is already too great.

中文

The theorem of Boltzmann may be applied not only to determine the distribution of velocity among the molecules, but to determine the

distribution of the molecules themselves in a region in which they are acted on by external forces. It tells us that the density of distribution of the molecules at a point where the potential energy of a molecule is ψ , is proportional to $e^{-\frac{\psi}{\kappa\theta}}$ where θ is the absolute temperature, and κ is a constant for all gases. It follows from this, that if several gases in the same vessel are subject to an external force like that of gravity, the distribution of each gas is the same as if no other gas were present. This result agrees with the law assumed by Dalton, according to which the atmosphere may be regarded as consisting of two independent atmospheres, one of oxygen, and the other of nitrogen; the density of the oxygen diminishing faster than that of the nitrogen, as we ascend.

中文

This would be the case if the atmosphere were never disturbed, but the effect of winds is to mix up the atmosphere and to render its composition more uniform than it would be if left at rest.

中文

Another consequence of Boltzmann's theorem is, that the temperature tends to become equal throughout a vertical column of gas at rest.

中文

In the case of the atmosphere, the effect of wind is to cause the temperature to vary as that of a mass of air would do if it were carried vertically upwards, expanding and cooling as it ascends.

中文

But besides these results, which I had already obtained by a less elegant method and published in 1866, Boltzmann's theorem seems to open up a path into a region more purely chemical. For if the gas consists of a number of similar systems, each of which may assume different states having different amounts of energy, the theorem tells us that the number in each state is proportional to $e^{-\frac{\psi}{\kappa\theta}}$ where ψ is the energy, θ the absolute temperature, and κ a constant.

中文

It is easy to see that this result ought to be applied to the theory of the states of combination which occur in a mixture of different substances.

But as it is only during the present week that I have made any attempt to do so, I shall not trouble you with my crude calculations. [中文](#)

I have confined my remarks to a very small part of the field of molecular investigation. I have said nothing about the molecular theory of the diffusion of matter, motion, and energy, for though the results, especially in the diffusion of matter and the transpiration of fluids are of great interest to many chemists, and though from them we deduce important molecular data, they belong to a part of our study the data of which, depending on the conditions of the encounter of two molecules, are necessarily very hypothetical. I have thought it better to exhibit the evidence that the parts of fluids are in motion, and to describe the manner in which that motion is distributed among molecules of different masses. [中文](#)

To show that all the molecules of the same substance are equal in mass, we may refer to the methods of dialysis introduced by Graham, by which two gases of different densities may be separated by percolation through a porous plug. [中文](#)

If in a single gas there were molecules of different masses, the same process of dialysis, repeated a sufficient number of times, would furnish us with two portions of the gas, in one of which the average mass of the molecules would be greater than in the other. The density and the combining weight of these two portions would be different. Now, it may be said that no one has carried out this experiment in a sufficiently elaborate manner for every chemical substance. But the processes of nature are continually carrying out experiments of the same kind; and if there were molecules of the same substance nearly alike, but differing slightly in mass, the greater molecules would be selected in preference to form one compound, and the smaller to form another. But hydrogen is of the same density, whether we obtain it from water or from a hydrocarbon, so that neither oxygen nor carbon can find in hydrogen molecules greater or smaller than the average.

The estimates which have been made of the actual size of molecules are founded on a comparison of the volumes of bodies in the liquid or solid state, with their volumes in the gaseous state. In the study of molecular volumes we meet with many difficulties, but at the same time there are a sufficient number of consistent results to make the study a hopeful one. 中文

The theory of the possible vibrations of a molecule has not yet been studied as it ought, with the help of a continual comparison between the dynamical theory and the evidence of the spectroscope. An intelligent student, armed with the calculus and the spectroscope, can hardly fail to discover some important fact about the internal constitution of a molecule. 中文

The observed transparency of gases may seem hardly consistent with the results of molecular investigations. 中文

A model of the molecules of a gas consisting of marbles scattered at distances bearing the proper proportion to their diameters, would allow very little light to penetrate through a hundred feet. 中文

But if we remember the small size of the molecules compared with the length of a wave of light, we may apply certain theoretical investigations of Lord Rayleigh's about the mutual action between waves and small spheres, which show that the transparency of the atmosphere, if affected only by the presence of molecules, would be far greater than we have any reason to believe it to be. 中文

A much more difficult investigation, which has hardly yet been attempted, relates to the electric properties of gases. No one has yet explained why dense gases are such good insulators, and why, when rarefied or heated, they permit the discharge of electricity, whereas a perfect vacuum is the best of all insulators. 中文

It is true that the diffusion of molecules goes on faster in a rarefied gas, because the mean path of a molecule is inversely as the density. But the electrical difference between dense and rare gas appears to be too great to be accounted for in this way. [中文](#)

But while I think it right to point out the hitherto unconquered difficulties of this molecular theory, I must not forget to remind you of the numerous facts which it satisfactorily explains. We have already mentioned the gaseous laws, as they are called, which express the relations between volume, pressure, and temperature, and Gay Lussac's very important law of equivalent volumes. The explanation of these may be regarded as complete. The law of molecular specific heats is less accurately verified by experiment, and its full explanation depends on a more perfect knowledge of the internal structure of a molecule than we as yet possess. [中文](#)

But the most important result of these inquiries is a more distinct conception of thermal phenomena. In the first place, the temperature of the medium is measured by the average kinetic energy of translation of a single molecule of the medium. In two media placed in thermal communication, the temperature as thus measured tends to become equal. [中文](#)

In the next place, we learn how to distinguish that kind of motion which we call heat from other kinds of motion. The peculiarity of the motion called heat is that it is perfectly irregular; that is to say, that the direction and magnitude of the velocity of a molecule at a given time cannot be expressed as depending on the present position of the molecule and the time. [中文](#)

In the visible motion of a body, on the other hand, the velocity of the centre of mass of all the molecules in any visible portion of the body is the observed velocity of that portion, though the molecules may have also an irregular agitation on account of the body being hot. [中文](#)

In the transmission of sound, too, the different portions of the body have a motion which is generally too minute and too rapidly alternating to be directly observed. But in the motion which constitutes the physical phenomenon of sound, the velocity of each portion of the medium at any time can be expressed as depending on the position and the time elapsed; so that the motion of a medium during the passage of a sound-wave is regular, and must be distinguished from that which we call heat. [中文](#)

If, however, the sound-wave, instead of traveling onwards in an orderly manner and leaving the medium behind it at rest, meets with resistances which fritter away its motion into irregular agitations, this irregular molecular motion becomes no longer capable of being propagated swiftly in one direction as sound, but lingers in the medium in the form of heat till it is communicated to colder parts of the medium by the slow process of conduction. [中文](#)

The motion which we call light, though still more minute and rapidly alternating than that of sound, is, like that of sound, perfectly regular, and therefore is not heat. What was formerly called Radiant Heat is a phenomenon physically identical with light. [中文](#)

When the radiation arrives at a certain portion of the medium, it enters it and passes through it, emerging at the other side. As long as the medium is engaged in transmitting the radiation it is in a certain state of motion, but as soon as the radiation has passed through it, the medium returns to its former state, the motion being entirely transferred to a new portion of the medium. [中文](#)

Now, the motion which we call heat can never of itself pass from one body to another unless the first body is, during the whole process, hotter than the second. The motion of radiation, therefore, which passes entirely out of one portion of the medium and enters another, cannot be properly called heat. [中文](#)

We may apply the molecular theory of gases to test those hypotheses about the luminiferous ether which assume it to consist of atoms or molecules. 中文

Those who have ventured to describe the constitution of the luminiferous ether have sometimes assumed it to consist of atoms or molecules. 中文

The application of the molecular theory to such hypotheses leads to rather startling results. 中文

In the first place, a molecular ether would be neither more nor less than a gas. We may, if we please, assume that its molecules are each of them equal to the thousandth or the millionth part of a molecule of hydrogen, and that they can traverse freely the interspaces of all ordinary molecules. But, as we have seen, an equilibrium will establish itself between the agitation of the ordinary molecules and those of the ether. In other words, the ether and the bodies in it will tend to equality of temperature, and the ether will be subject to the ordinary gaseous laws as to pressure and temperature. 中文

Among other properties of a gas, it will have that established by Dulong and Petit, so that the capacity for heat of unit of volume of the ether must be equal to that of unit of volume of any ordinary gas at the same pressure. Its presence, therefore, could not fail to be detected in our experiments on specific heat, and we may therefore assert that the constitution of the ether is not molecular. 中文

(11, 374-377; 1875)

* A lecture delivered at the Chemical Society, Feb. 18, by Prof. Clerk Maxwell, F. R. S.

† Over de continuïteit van den gas en vloeistof toestand. Leiden: A. W. Sijthoff, 1873.

‡ “A method of geometrical representation of the thermodynamic properties of substances by means of surfaces.” *Transactions of the Connecticut Academy of Arts and Sciences*, vol. II, Part 2.

关于物体分子构成的动力学证据*

麦克斯韦

在这篇文章中，克拉克·麦克斯韦介绍了从基本原理（现在的名字是统计力学）出发研究气体和液体性质的最新进展。此前，麦克斯韦提出了他的气体动力学理论，这是他作出的决定性的贡献。在本文中他报道了鲁道夫·克劳修斯等其他研究人员的工作。克劳修斯引入了“位力”这个理论物理量，用来表示所有粒子对的粒子间距离与粒子间引力或斥力乘积的总平均。麦克斯韦在这篇文章中还提到了另外两个人的工作，其中一个在当时还没什么名气的研究生约翰内斯·迪德里克·范德瓦尔斯，另一个是美国物理学家约西亚·威拉德·吉布斯，这两人后来都成了研究物质体系基本行为特征的领袖人物。

英文

I

任何一种现象，一旦可以被视为某种适用于其他现象的普遍原理的实例，我们就可以说这种现象得到了解释。然而，解释包括很多不同层面，要视所采用原理的普适程度而定。因此，第一个观察到将水泼入火中这种现象的人，在发现结果总是相似的而且这些结果并不取决于水和火之间那瞬息万变、反复无常的不相容性时，便会获得一定程度的精神满足。这是一种最低层次的解释，在这种解释中，以上现象所涉及的分还包含其他现象，而这些现象只是发生的时间和地点不同，所涉及的原理却是非常普适的，因此时间和地点并不属于能够决定自然过程的条件。另一方面，当某一物理现象能够被完全描述为物质系统结构或运动的变化时，我们就可以说这种现象得到了完整的动力学解释。我们想不出还有什么更进一步的解释是必要的、有用的或者可能的，因为一旦我们了解了结构、运动、质量和力这些词的意义，便会发现它们所表示的

意义如此基本，以至于无法再用其他概念来解释它们。

英文

化学家们研究的现象，大部分还没有得到完整的动力学解释。

英文

很多化合物分子的图示或模型已经建立。它们都是化学家根据可以说明或解释的化学现象的几何关系努力猜想物质系统的结构而得到的结果。不过，这些图示只不过是构成分子的不同成分束缚在一起的各种不同的紧密程度的符号表示而已，没有一位化学家敢说他能从中看出更多的东西。

英文

另一方面，在天文学中，天体的结构和运动所具有的尺度是我们可以直接观测来确定的。牛顿证明了观测到的运动显示出所有物体之间都有不断彼此靠拢的趋势，他建立的万有引力定律不仅解释了观测到的我们自身所在系统的运动，而且使我们能够计算出具有任意量值的天文学对象所组成的系统的运动情况。

英文

从天文学转向电学，我们仍然可以观测带电体的结构和运动，并遵循严格的牛顿式方法来推导出它们的相互作用力。但是我们发现这种力依赖于所谓的电的分布。因此，建立一种关于电作用不可见过程的、被高斯称为“统一表象”的理论，就成为这门科学的迫切需要。

英文

在试图将动力学方法推广以用于对化学现象的解释时，我们必须形成关于大量物质系统的结构和运动的观念，而其中每一个物质系统都小到无法直接观测的程度。事实上，我们只能通过观测那些看不见的结构部分的外部作用来确定其内部结构。

英文

主要用来进行此类研究的方法是先建立一个假说，然后计算如果该假说成立会产生什么结果。若这些结果与实际现象相吻合，我们就说这个假说得到了确证，至少在没有其他人提出与客观现象更一致的另一种假说之前，是可以这样说的。

英文

之所以有如此多的物理理论依靠假说的方式建立起来，是因为理论家早期没有获得具有足够普适性的方法和术语来表达他们归纳出的结果。受此限制，他们要么将观点表达得含糊不清以至于毫无用处，要么

用另一种形式表达观点，而这种形式的细节只能靠非常规的想象力来弥补。

英文

与此同时，数学家在其本能（这种本能使他们将自身才智孕育出的丰硕果实供给他人）的驱使下已经发展出了具有充分普适性的关于物质系统的动力学理论。

英文

在所有关于物体构成的假说中，最可信的无疑是这样一种假说：它除了假定物体构成物质系统之外绝无更多假定，并仅就观测到的现象在合理范围内所提供的有关物质系统的条件和联系等信息进行推导。

英文

在合理地阐明和解释这种物理假说方法的实例之后，我们受到的对科学界人士推理不严谨的抱怨将会变得很少，并且相应的归纳哲学方法也不会再被人嘲笑为凭空臆测了。

英文

迄今为止，物体构成理论中只有一小部分已经通过已知的事实被归纳为精确的结论。要通过合理的实验和严格的论证引导科学活动沿着十分合理的道路前进，就需要一种战略技巧，这种技巧可遇不可求，即使对于那些凭借原始观测与丰富联想进行科学研究的人来说也是一样。下面的事实并不会贬低科学先驱的成就，即他们在未知领域的开拓工作，这些开拓工作曾经一度被隔离于有着已确定的作用基础的交流体系之外，而这个交流体系正是任何科学持续发展的唯一保障。

英文

要研究物体构成，我们从一开始就不得不处理看不见的微粒。因为不管我们对于分子和原子得到的最终结论将是什么，现在我们已经得到了实验上的证据，可以证明物体可以被分割成小到无法察觉的部分。

英文

由此，如果我们细心地注意到微粒这个词只表示物体的一小部分，而且毫不涉及关于物质终极可分性的假设，我们就可以认为物体是由微粒组成的，我们还可以断言，在物体或者具有可观测尺度的物体的某一部分中，微粒的数量是非常大的。

英文

下面我们还需要一种可以研究由大量微粒组成的物质系统的动力学

方法，这就要形成一种关于微粒的结构、运动以及作用在粒子上的力的概念，并从动力学理论中推导出在系统的可见部分中可观测到的现象，尽管这些现象是由不可见微粒的运动和结构决定的。 [英文](#)

进行这种研究必不可少的动力学原理是由多位动力学奠基人发展起来的，从伽利略、牛顿到拉格朗日和拉普拉斯；而将这些原理应用于分子研究，则很大程度上是波恩的克劳修斯教授的贡献，除了复杂的计算结果之外，他最近提出的一种新的动力学观点，给我们的研究工作带来了很大的帮助。借助这种观点，我希望我们可以不用大量的符号演算也能得到一些重要的结论。 [英文](#)

现在我必须提醒大家注意，克劳修斯方程具有如下形式：

$$pV = \frac{2}{3}T - \frac{2}{3}\Sigma\Sigma\left(\frac{1}{2}Rr\right)$$

其中， p 表示某种流体的压力， V 表示盛放流体的容器的体积。由玻意耳定律可知，对于恒温条件下的气体，乘积 pV 在不同的体积和压力下基本保持不变。可见，方程的左边，是两个直接观测量的乘积。 [英文](#)

方程的另一边由两项组成，第一项由微粒的运动决定，第二项由微粒间的相互作用力决定。 [英文](#)

T 这个量指系统的动能，或者换一种说法，是由于系统各部分的运动而具有的那部分能量。 [英文](#)

微粒的动能是其质量与速率平方的乘积的一半，而系统的动能则是其各部分动能的总和。 [英文](#)

在第二项中， r 表示任意两个微粒之间的距离， R 表示它们之间的吸引力。（如果作用力为排斥力或者压力，则 R 取负值。） [英文](#)

$\frac{1}{2}Rr$ 这个量，即引力与彼此吸引的微粒之间距离的乘积的一半，克劳修斯将其定义为引力的位力。（对于压力和排斥力，位力取负值。）

[英文](#)

克劳修斯首次指出了这一物理量的重要性。通过给这一物理量指定名字，克劳修斯大大推动了他的方法在物理解释中的应用。 [英文](#)

系统的位力是系统中每一对微粒之间位力的总和，可以表示为双重求和 $\sum\sum(\frac{1}{2}Rr)$ ，意思是要得到每一对微粒之间的 $\frac{1}{2}Rr$ 值，并将结果累加起来。 [英文](#)

克劳修斯通过简单的数学过程建立了这一方程，这里我不需要以此来烦扰各位，因为今晚我们不是在研究数学问题。不过我们还是可以看到，方程指出有两个因素可能会影响流体对容纳它的容器的压力：流体中微粒的运动倾向于增大压力，而微粒间的吸引力倾向于减小压力。

[英文](#)

由此，我们可以将流体的压力归结为流体中微粒的运动或者微粒间的排斥力。 [英文](#)

让我们用克劳修斯的结果来验证一下下面的理论：气体压力完全源于一个微粒施加在另一个微粒上的排斥力，而就恒容容器中的气体而言，这些微粒是真正静止的。 [英文](#)

在上述情况中，位力必定为负值，又由玻意耳定律可知压力与体积的乘积为常数，则等量恒温的气体，不论其体积是多少，位力也一定是常数。由此可知，两个微粒之间的排斥力与距离的乘积 Rr 必为常数，换言之，排斥力必定与距离成反比。然而，牛顿已经指出这一定律不适用于分子间作用力的情况，因为它将使物体中相隔较远的部分间的相互作用比相邻的部分间的相互作用更强。实际上，我们只需注意到，如果 Rr 是常数，那么每一对微粒的位力都一定是相同的，于是系统的位力一定会正比于系统中微粒的对数——即正比于微粒数的平方，或者说正比于容器中气体数量的平方。根据这一定律，相同密度的气体在不同容器中的压力也是不同的，在较大容器中的压力会比在较小容器中的压力更大，而在开放的大气中的压力比在任何普通容器中的压力都大。 [英文](#)

因此，气体的压力无法通过假定微粒间存在排斥力进行解释。

[英文](#)

这样一来，气体的压力就一定完全是完全地或部分地依赖于微粒的运动。[英文](#)

如果我们假定微粒间没有任何相互作用，那么就没有位力存在，方程可简化为如下形式：

$$Vp = \frac{2}{3} T$$

如果用 M 表示气体的总质量， c^2 表示微粒速率的均方，我们就可以将方程写作——

$$Vp = \frac{1}{3} Mc^2,$$

或者用文字表述为，体积与压力的乘积是质量与速率均方乘积的1/3。现在我们先假设，速率的均方仅取决于温度，那么这个方程恰好就是玻意耳定律，后面我们将通过独立的过程来证明。[英文](#)

但是我们知道大部分常见气体都会偏离玻意耳定律，尤其是在低温和高密度的状态下。现在我们再来看看刚才在作为产生气体压力的唯一原因被提出时，已经被我们否定的微粒间存在作用力的假说，在作为偏离玻意耳定律的原因时是否会与实验不一致。[英文](#)

当气体处于极稀薄的状态时，在任一微粒周围给定距离之内的微粒数量将正比于气体密度。因此，一个微粒作用于其他微粒而产生的位力将随密度变化，单位体积内的总位力将随密度的平方变化。[英文](#)

设密度为 ρ ，将方程两边同除以 V ，我们得到——

$$p = \frac{1}{3} \rho c^2 - \frac{2}{3} A \rho^2,$$

其中 A 这个量在密度很小时近似为常数。[英文](#)

勒尼奥的实验表明，大多数气体在密度增大时，其压力会下降到低于玻意耳定律的计算值。因此位力必定是正的；也就是说，微粒间的相互作用必定以引力为主，而且这种作用减小压力的效果在开始的时候一定是近似与密度的平方有关。[英文](#)

另一方面，当压力继续增大，物质最终将达到另一种状态，即压力急剧增大但密度只有很小的增加。这表明此时位力为负值，或者换句话说，此时微粒间的相互作用主要为斥力。我们可以由此确定，在任何可感知的尺度中，两个微粒之间的相互作用都是十分微弱的。随着微粒彼此靠近，它们之间的相互作用首先表现为引力，引力达到最大值后开始减小，最终转变为极大的斥力，以至于没有任何可获得的力能够将微粒间的距离减小到零。 英文

源于微粒间这种相互作用的压力与密度之间的关系就是这样的。

英文

随着密度从零开始逐渐增大，一开始压力几乎完全取决于微粒的运动，因此几乎与玻意耳定律计算得到的压力精确地吻合。随着密度继续增加，微粒间相互吸引力的影响逐渐体现出来，这使得压力的增大小于根据玻意耳定律预计的值。如果温度很低，吸引力的影响会大到可以与运动的影响相抗衡的程度，那么压力就不再总是随着密度的增加而增大，而是在达到一个最大值后开始减小。 英文

最终，随着微粒的平均距离继续减小，斥力的影响将胜过引力的影响，而压力将会增大到超出玻意耳定律所预计的值，而且此时很小的密度增加也会导致压力的急剧增大。 英文

由此，压力与体积之间的关系可以用曲线A B C D E F G来表示，其中横坐标代表体积，纵坐标代表压力。 英文

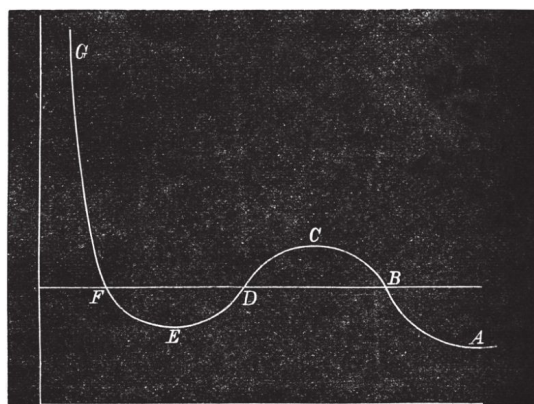


图1 英文

随着体积缩小，压力先增大到 C 点，然后减小到 E 点，最终将随体积缩小而无限增大。 [英文](#)

到目前为止，我们始终假设在实验过程中介质的每一部分都具有相同的密度。不过，这在实际中是不可能的，我们能够从外部施加于介质的唯一限制，仅仅是确保整个介质都置于确定的容器之中。因此，如果介质有可能自身调整为各处密度不同，我们也无法阻止。 [英文](#)

B 点和 F 点代表介质的两种状态，其压力相同但密度相差甚远。全部介质可从状态 B 到达状态 F ，不经过中间状态 $C D E$ ，而是直接由状态 B 一点一点地转化为状态 F 。这样，整个介质的连续变化状态对应于图中直线 $B F$ 上的点， B 点代表介质完全处于稀薄状态， F 则代表介质完全处于凝聚状态。这就是气体或者蒸气在液化过程中发生的现象。 [英文](#)

因此，一般情况下，恒定温度时压力与体积的关系对应于图中的折线 $A B F G$ 。不过，如果在液化过程中小心地避免介质与蒸气接触，就可能可以使介质保持在液态，并达到图中 E 点和 F 点之间的曲线部分所代表的状态。也有可能可以设计出某种阻止蒸气凝聚的方法从而达到曲线 $B C$ 上的点所代表的状态。 [英文](#)

假设的曲线中从 C 点到 E 点的部分代表本质上不稳定的状态，因此是无法实现的。 [英文](#)

现在，让我们设想介质始终以均匀的状态沿着假设的曲线 $B C D E F$ 从 B 变化到 F ，并以蒸气和液体混合的形式沿着直线 $F B$ 返回。因为温度一直是恒定的，所以其间不会有热能转化为功，而转化为功的热能对应于区域 $F D E$ 与 $B C D$ 的面积差。因此，在给定温度下使蒸气压力达到最大的条件，就是直线 $B F$ 与上方和下方曲线围成的面积相等。 [英文](#)

温度越高，由运动决定的那部分压力与由微粒间作用力决定的部分相比就越大。因此，随着温度升高，曲线的凹陷变得不明显，当温度达到某一个值时，曲线不再凹陷而在某一点达到水平线的位置之后曲线就像前面那样上升了。这个点称为临界点。安德鲁斯已经用巧妙的研究方法确定了碳酸的临界点。临界点对应于确定的温度、压力和密度。

[英文](#)

在更高的温度下，曲线始终是向上倾斜的，在从最稀薄到最稠密的状态变化过程中不发生液化。 [英文](#)

关于液态与气态连续性的分子理论构成了一篇极具才华的论文的主题，论文的作者是莱顿大学的毕业生约翰内斯·迪德里克·范德瓦尔斯先生†。尽管我觉得他在某些地方犯了一些数学错误，而且他的最终结果也确实不是对真实分子间相互作用的完整表达，但是他对这一难题所作的努力表现了他非凡的才华和勇气，以至于他的工作不可能不对分子科学产生重要的推动作用。确实有不只一位研究者受此驱使而去学习这篇文章撰写时所用的荷兰语。 [英文](#)

物质不同状态间纯粹的热力学联系不属于我们的主题，因为它与这些关于分子的具体理论无关。不过，我决不能忘记提及一项极为重要的，由美国耶鲁大学的威拉德·吉布斯教授作出的热力学方面的贡献‡，他利用一个模型给我们提供了一种极其简单又十分令人满意的表示不同物态间关联的方法。借助这个模型，那些长期以来阻碍我本人和其他人努力的难题可能立刻就会迎刃而解。 [英文](#)

II

现在让我们回过头来看看极稀薄状态的气体，在这种状态下压力完全来源于气体微粒的运动。由于体积、压力和质量都是可观测量，因此很容易利用克劳修斯方程计算出微粒速率的均方。假设每种微粒具有相同的速率，则在0°C时，氧分子的速率为每秒461米，氮分子为每秒492米，而氢分子为每秒1,844米。 [英文](#)

已经有多位学者多次提出过用气体微粒对容器表面的撞击来解释气体对容器的压力。不过，我们一直不能解释为什么从未观测到气体以接近于上面所提到的速率散布到大气中的现象，直到克劳修斯通过对大量微粒的运动的全面研究发展了现代分子科学的方法和观念。 [英文](#)

我们得益于他提出的一个概念，即一个气体分子在与其他分子相继发生两次碰撞之间所经过路程的平均长度。一旦看到每个气体分子是如何在经历了一段极短的路程后与另一个分子相撞，随后气体分子又沿着完全不同的方向开始新的旅程，那么很明显的就是：气体扩散的速率不

仅依赖于分子的速度，还与分子在相继发生的碰撞之间途经的距离有关。[英文](#)

关于克劳修斯对分子科学的特殊贡献，我还有很多要说。最主要的是，他通过展示如何用数学方式处理含无数分子的运动系统从而开创了数学物理的新领域。[英文](#)

至少在早期的研究中，克劳修斯并没有试图去确定同一气体中的所有分子是否都具有相同的速率，或者如果它们的速率不等，其分布是否应遵循某种规律。他的第一个假说似乎假定所有分子的速率都是相等的。不过显而易见的是，如果碰撞发生在大量分子之间，那么即使它们的速率开始时是相等的，之后也会变得不相等，因为除了在某些几乎无法满足的条件下，两个碰撞前具有相同速率的分子在碰撞后总会获得不同的速率。通过将分子按其速率分组，我们就只需记录不同组内分子数量的增加或减少，而不必完成跟踪每一个分子的所有碰撞这项不可能完成的任务。[英文](#)

利用这种无论从实验角度还是数学角度来说都是唯一可行的方法，我们从严格的动力学方法转到了统计和概率的方法上。[英文](#)

当两个分子发生碰撞时，它们就会从原本所在组的一对转变成另一组的一对，而且在同时发生大量碰撞时，平均来看，同一时间段内进入某一个组的分子数量，不会多于或少于离开该组的分子数量。当系统达到这种状态时，分子在各组的分布一定符合某种确定的规律。[英文](#)

我在了解了克劳修斯的研究工作之后，便立即努力探求这一规律。[英文](#)

我在1860年发表的结果后来由路德维希·玻尔兹曼博士进行了更为严格的研究，他还将他的方法应用于对化合物分子运动的研究。数学研究，例如所有关于概率统计的科学部分，虽然有些困难，却不无裨益。从物理角度来说，数学方法的某些推论是非常正确的，似乎可以说明所选假说是正确的，而另一些却与已知的实验结果相违背，这使我们不得不承认，到目前为止，我们遗漏了关于分子碰撞物理理论完整表述中的某些核心部分。[英文](#)

现在我必须努力为各位介绍这方面研究的现状，不过，我们不会涉及其中的数学证明。 [英文](#)

我必须从同种分子中速度分布的一般规律开始说起。 [英文](#)

如果从图中选择一个固定的点，从这点出发画一条线来表示速度的方向和大小，并在线段末端画出端点，那么端点的位置就表示分子的运动状态。 [英文](#)

如果我们对所有分子作同样处理，那么整张图上将画满了点，某些位置的点会比其他位置的点多。 [英文](#)

可以看出，这些点的分布规律与观测或调节中经常出现的误差的分布规律是相同的。 [英文](#)

你面前这张图中的点可以用来表示分子的速度，或者对同一颗恒星位置的不同观测结果，或者位于目标靶心周围的弹洞，上述这些具有相同的分布方式。 [英文](#)

分子速率的取值范围是从零到无限大，因此说到分子的平均速率我们必须先定义我们指的是什么。 [英文](#)

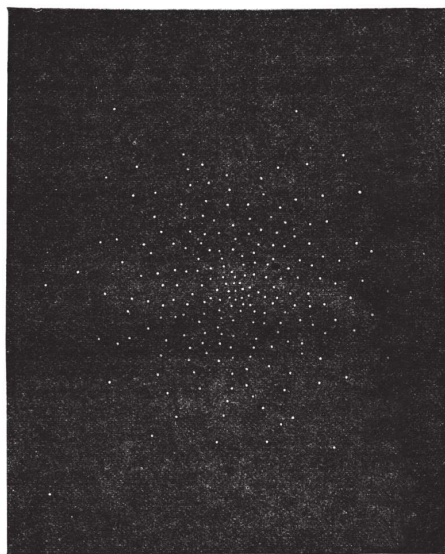


图2．速度图像 [英文](#)

为了便于比较和计算，最有用的量叫作“均方速率”。这个量的平方是所有分子速率平方的平均值。 [英文](#)

这就是上面给出的利用不同气体性质计算得到的速度。以均方速率运动的分子具有的动能等于介质内全体分子的平均动能，并且若以此速率运动的单个物体的质量等于气体的总质量，那么该物体与气体具有相同的动能，只是前者具有可见的形式并可直接用于做功。 [英文](#)

如果同一容器中包含不同种类的分子，其中一些具有比较大的质量，那么根据这项研究，这些分子的速度分布方式应满足每种分子具有相同的平均动能，不管其质量是大还是小。 [英文](#)

这里我们用到的可能是动力学方法最重要的应用，即将它应用于化学科学。比如，假定我们将两种气体置于同一容器中。分子运动的最终分布形式应满足两种气体中每一种的单个分子的平均动能相等。正如我们所知，这种最终态也是等温态。由此，两种气体具有相同温度的条件，就是两种气体中单个分子的平均动能相同。 [英文](#)

现在，我们已经指出，气体的压力是单位体积动能的 $\frac{2}{3}$ 。因此，如果两种气体具有相同的压力和温度，那么它们每单位体积的动能以及每个分子的动能也是相同的。由此，两种气体单位体积内必定含有相同数量的分子。 [英文](#)

这一结果与盖·吕萨克提出的等容定律是一致的。不过，到目前为止该定律只基于化学证据，不同物质的相对分子质量已经从物质参加化合反应时所占据的比例中推导出来了。现在已经用动力学原理证明了该定律。分子被定义为扰动运动中作为一个整体运动的物体的一小部分。这是一个纯粹的动力学定义，与任何化合实验无关。 [英文](#)

在标准的温度和压力下，气态介质的密度正比于该气体按以上定义的一个分子的质量。 [英文](#)

这样，我们就有一种可以估计气态时不同物质的相对分子质量的可靠方法。这种方法比那些建立在电解或者比热基础上的方法更可靠，因为我们已经掌握的关于扰动运动条件方面的知识比关于电解或者分子

结构内部运动的知识更完备。 [英文](#)

现在我必须谈谈这些分子的内部运动，因为目前气体动力学理论遇到的最大困难就在这部分。 [英文](#)

迄今为止我们考虑的只是分子质心的运动。现在我们不得不考虑分子组分相对于质心的运动。 [英文](#)

如果我们假定分子是由原子构成的，并且每个原子都是所谓的质点，那么每个原子都可以在3个不同且独立的方向上运动，这对应于空间的3个维度，因此要确定分子中所有原子结构和位置所需的变量数就是原子个数的3倍。 [英文](#)

不过，对数学研究来说，假定分子是由原子构成的并不是一个基本假设。全部的前提假设只是，分子的位置和结构可以用一定数量的变量完整地表达。 [英文](#)

让我们将这个数设为 n 。 [英文](#)

在这些变量中，有3个是用来确定分子质心位置的，而其余 $n-3$ 个则用来确定相对于质心的分子结构。 [英文](#)

n 个变量的每一个都对应于一种不同的运动。 [英文](#)

质心的平移运动有3个分量。 [英文](#)

各部分相对于质心的运动则包含 $n-3$ 个分量。 [英文](#)

分子的动能可以看作是由两部分组成——其中一部分是假定整个分子的质量集中于其质心所产生的，另一部分是各部分相对质心运动所产生的。第一部分称为平动动能，第二部分称为转动和振动动能。上述量的总和就是分子运动的总能量。 [英文](#)

正如我们所知，气体的压力只由平动动能决定。比热则依赖于温度升高时动能与势能的总增加量与温度增量的比值。 [英文](#)

克劳修斯早就指出，如果我们能够通过实验获得恒压比热与恒容比

热的比值，就能确定总能量增量与平动动能增量的比值。

[英文](#)

但是，他并没有试图先验性地确定两部分能量的比值，尽管他提出了一个极有可能成立的假说：对于一种给定的物质，两部分能量的平均值总是具有相同的比值。他将这一比值的具体数值留待实验确定。

[英文](#)

1860年，我基于分子是不变形的弹性体的假说研究了两部分能量的比值。我惊讶地发现，不论分子是何种形状，只要它们不是绝对光滑和完美球状，那么两部分能量的比值就一定总是相同的，实际上这两部分能量是相等的。

[英文](#)

这一结果被玻尔兹曼的研究工作所证实，他给出了具有 n 个变量的分子在一般情况下的结果。

[英文](#)

他发现，相同温度下任何种类的分子都具有相同的平均平动动能，运动的总能量与平动动能之比为 $n:3$ 。

[英文](#)

对于刚体来说 $n = 6$ ，这使得运动的总能量为平动动能的2倍。

[英文](#)

但是，如果分子能够在外力作用下改变形状，它就一定可以储存势能，而如果外力是能保证分子的稳定性的那种，当内部运动的平均能量增加时，平均势能也会增加。

[英文](#)

因此，随着温度升高，平动动能、内部运动能量和势能的增量分别为3， $(n-3)$ 和 e ，其中 e 是取值为正的未知量，其数值取决于将分子各组成部分束缚在一起的力的定律。

[英文](#)

当物体的体积保持不变时，加热的效果是增加总能量。我们由此给出恒容气体的比热——

$$\frac{1}{2J} \frac{p_0 V_0}{273^\circ} (n + e)$$

其中 p_0 和 V_0 是零摄氏度或绝对温度 273° 时单位质量的压力和体积，而 J 则是热的动力学当量。恒压条件下的比热为

$$\frac{1}{2J} \frac{p_0 V_0}{273^\circ} (n + 2 + e)$$

英文

对于那些有相同复杂程度的分子， n 值是相同的， e 值可能是相同的。
英文

如果情况就是如此，那么根据杜隆-珀蒂定律，比热与比重成反比，这是一条在一定精度范围内已经被实验证明了的定律。
英文

但是，如果我们采用勒尼奥所发现的实际比热值并将其与此公式进行比较就会发现，对空气和其他几种气体， $n + e$ 的值不会超过4.9。而对碳酸和水蒸气来说这个值则大一些。如果将计算所得的比热之比值

$$\frac{2 + n + e}{n + e}$$

与实验确定的比值相比，我们得到相同的结果，即1.408。
英文

此时，我们将面临分子理论中最大的困难，也就是，如何解释等式 $n + e = 4.9$ 。
英文

如果我们假设分子是不可分割的质点——没有转动能量或者内部运动——那么 n 为3而 e 为0，比热的比值是1.66，而这个值对于任何实际气体来说都太大了。
英文

但是，通过光谱仪我们了解到，分子可以进行周期固定的振动。因此分子不可能只是一个质点，而应是一个结构可以改变的体系。这一体系的变量不可能少于6个。这使得比热比值的最大值是1.33，而这个结果对于氢气、氧气、氮气、碳氧化物、氮氧化物和氢氯酸来说都太小了。
英文

但是光谱仪告诉我们某些分子可以进行多种不同类型的振动。因此它们必然是具有相当复杂程度的体系，具有的变量数远大于6。那么，每增加一个变量，都会在不影响外部压力的前提下引入一些附加的内部运动的能力。因此，不论是在恒压还是恒容条件下计算，每增加一个变

量都会使比热增加。 [英文](#)

分子以势能形式储存能量的能力也是如此。但是，当我们假定分子仅由两个原子组成，计算得到的比热值就已经太大了。于是，分子的复杂程度每增加一点，都只会加大使比热的观测值与计算值相一致的难度。 [英文](#)

现在我已将我认为是分子理论遇到的最大困难呈现在各位面前。玻尔兹曼曾经建议，应该从分子与围绕在其周围的以太介质的相互作用中寻求解释。不过，要是我们借助于这种介质的话，恐怕只会使已经过大的比热计算值变得更大。 [英文](#)

玻尔兹曼定理不仅可以用于确定分子的速度分布，还可以用于确定在外力作用下分子自身在一个区域中的分布。它告诉我们，在分子势能为 ψ 的一点，分子的分布密度正比于 $e^{-\frac{\psi}{\kappa\theta}}$ ，其中 θ 为绝对温度，而 κ 对于所有气体都是常数。由此可知，如果同一容器中的几种气体受到外力（例如重力）作用，每一种气体的分布与没有其他气体存在时是一样的。这一结果与道尔顿提出的定律是一致的，根据这个定律，大气可以被视为是由两种独立的气体组成，一种为氧气，另一种为氮气；随着海拔升高，氧气的浓度比氮气的浓度减小得更快些。 [英文](#)

以上是大气丝毫不受扰动的情况，而风的影响会将大气混匀，使其组成比保持静止时更均匀。 [英文](#)

玻尔兹曼定理的另一推论是，静止状态的气体在垂直方向上温度趋于一致。 [英文](#)

对于大气来说，风的影响导致温度变化，例如，若一定质量的气体垂直向上运动，那么它在上升过程中会膨胀并会冷却。 [英文](#)

然而，除了给出这些我已经于1866年就以不那么精巧的方法获得并发表的结果之外，玻尔兹曼的定理似乎还开辟了一条通向更纯粹的化学领域的道路。因为，如果气体是由大量相似的系统构成，每一个系统都可以假定为具有不同能量的不同状态，定理告诉我们每一状态中系统的数量正比于 $e^{-\frac{\psi}{\kappa\theta}}$ ，其中 ψ 表示能量， θ 表示绝对温度，而 κ 是一个常数。

英文

容易看出，这一结果应当被用于发生在不同物质混合物中的组合的状态理论。不过，由于这项工作是我这个星期才刚刚开始，我还不想以我粗糙的计算结果来搅扰诸位。

英文

我一直将论题限制在分子研究领域的一个很小的范围内。我并没有提及关于物质扩散、运动以及能量的分子理论，因为，尽管这些结果，尤其是关于物质扩散和液体蒸发的结果，对很多化学家来说极有吸引力，并且从这些结果中我们可以推导出重要的分子数据，但这些数据依赖于两个分子碰撞的条件，因而属于我们研究工作中必然具有很多假设性的部分。我认为，还是展示一下能表明流体各部分运动的证据，并且描述一下此运动在不同质量的分子中的分布情况更好些。

英文

为表明同种物质的所有分子都具有相同的质量，我们就要谈到格雷姆引入的透析法，用这种方法可以通过一个多孔塞进行过滤，将两种不同密度的气体分离。

英文

如果在一种气体中存在不同质量的分子，将同样的透析过程足够多次地重复之后，我们就可以得到两部分气体，其中一部分的平均分子质量比另一部分的大。这两部分气体有不同的密度和化合量。现在，也许可以说，没有谁曾以足够精细的方式对每一种化学物质进行过这一实验。然而自然过程在持续不断地进行着这种类型的实验。如果同种物质具有十分相似但质量略有差别的分子，那么其中质量较大的分子将会被优先选择来形成一种化合物，而质量较小的分子则形成另一种。但是，无论是从水中还是从碳氢化合物中得到的氢都具有相同的密度，因此，氧和碳都不能在氢分子中找到大于或小于平均质量的个体。

英文

目前已有的对分子实际大小的估计都建立在将物体固态或液态时的体积与气态时的体积相比较的基础之上。在对分子体积的研究中我们遇到了很多困难，但同时也得到了很多可靠的结果，这使研究充满了希望。

英文

对于分子可能的振动，相关理论的研究尚未开始，它本应在不断将动力学理论与光谱证据相比较的帮助下展开。用光谱工具和算法武装

起来的才智之士，一定会发现一些与分子内部结构有关的重要事实。

英文

观测到的气体的透明度看来似乎很难与分子研究的结果一致。

英文

一种认为气体是由间隔距离与其自身直径符合适当比例的分散小球组成的气体分子模型，只能允许极少量的光穿透100英尺的距离。

英文

不过，要是我们还记得与光的波长相比分子尺寸很微小，我们就采用瑞利勋爵关于波与微小球体间相互作用的某些理论研究。他的研究表明，气体的透明度如果只受分子存在的影响，就会比我们有any理由能够去相信的还要大得多。

英文

一项几乎还没有人尝试过的更加困难的研究，是与气体的电学性质有关。还没有人能够解释为什么稠密的气体是非常良好的绝缘体，为什么气体在稀释或加热时可以放电，而完全的真空却是最好的绝缘体。

英文

的确，稀薄气体中的分子扩散会进行得更快一些，因为分子运动的平均路程反比于密度。但是稠密气体与稀薄气体的电学差异似乎非常大以至于无法从这个角度来解释。

英文

虽然我认为指出这种分子理论目前尚无法克服的困难是应该的，但我绝对不会忘记提醒诸位它已经令人满意地解释了大量问题。我们已经提到过气体定律，正如我们所说，它表达了气体的体积、压力与温度之间的关系，以及盖·吕萨克的极其重要的等容定律。可以认为关于这些定律的解释是完整的。分子比热定律已被实验相对粗略地验证了，而对它的完整解释则有赖于拥有比今天更完备的关于分子内部结构的知识。

英文

不过，由这些探索得到的最重要的结果是关于热现象更加明确的概念。首先，介质的温度由介质中单个分子的平均平动动能来度量。在两种介质有热交换时，以此确定的温度有变得一致的倾向。

英文

其次，我们知道了如何将所谓的热运动与其他类型的运动区分开。我们所谓的热运动的特性是完全无规则；也就是说，在任一给定时刻，一个分子的速度的方向和大小不可能用时间和现在分子所处的位置表示。

[英文](#)

另一方面，在物体的可视运动中，物体的任一可视部分所含全部分子的质心速度，就是所观测到的该部分的速度。不过，分子也可能由于被加热而具有不规则的扰动。

[英文](#)

同样地，在声音的传播过程中，物体不同部分的运动通常由于过于细微和过于快速变化而难以被直接观测。不过，在产生声音这一物理现象的运动过程中，介质中每一部分在任意时刻的速度都可以用位置和所经过的时间表示出来；因此在声波传播过程中介质的运动是规则的，必然不同于我们所说的热运动。

[英文](#)

然而，如果声波不是以整齐有序的方式向前传播并使其所经之处的介质归于静止，而是遇到阻力从而将运动耗损在无规则的激发中，这种无规则的分子运动就无法再以声音的形式在一个方向上快速地传播，而只能以热的形式留在介质中，直到通过缓慢的传导过程流向介质较冷的部分。

[英文](#)

被我们称为光的那种运动，尽管比声音运动更加细微和快速变化，但也和声音一样是非常规则的运动，因此不是热运动。以前被称为热辐射的物理现象在物理本质上与光是一样的。

[英文](#)

辐射在到达介质的某一部分后，就会进入并穿过该部分，再从另一端出现。该部分介质在传导辐射时处于一种特定的运动状态，而一旦辐射穿过该部分介质，该部分介质便会回到先前的状态，而运动完全转移到了介质中新的部分。

[英文](#)

现在，我们称为热的这种运动，不会自发地从一个物体进入另一个物体，除非在整个传导过程中，第一个物体总是比第二个物体的温度高一些。因此，从介质的一部分完全流出再进入另一部分的辐射运动，就不适宜被称作热了。

[英文](#)

我们可以用气体分子理论去检验那些假定光以太是由原子或分子组成的假说。 [英文](#)

那些敢于描绘光以太组成的人们也曾假定它是由原子或分子组成的。 [英文](#)

将分子理论应用于这类假说会导致相当令人惊讶的结果。 [英文](#)

首先，以太分子只会是气体本身。如果我们愿意的话，我们可以假定每个以太分子都是一个氢分子的千分之一或百万分之一，并且它们可以自由穿越任何常见分子的间隙。但是，正如我们已经看到的，普通分子的扰动与以太分子的扰动之间会自发地建立平衡。换句话说，以太与其中的物体会趋于温度相同的状态，那么以太就会服从诸如压力和温度等常见的气体定律。 [英文](#)

以太除了具有气体的性质以外，根据杜隆和珀蒂建立的定律，相同压力下，单位体积以太的热容与单位体积任何普通气体的热容相等。因此，在比热实验中不可能检测不到以太的存在，从而我们可以断言以太不是由分子构成的。 [英文](#)

（王耀杨 翻译；李芝芬 审稿）

* 2月18日，克拉克·麦克斯韦教授（皇家学会会员）在化学学会所作的讲座。

† 《论液态和气态的连续性》，莱登赛特霍夫出版社，1873年。

‡ 《借助曲面表示物质热力学性质的几何描述法》，《康涅狄格艺术与科学学会学报》，第2卷，第2部分。

Maxwell's Plan for Measuring the Ether

One of the most remarkable of Maxwell's scientific exploits was a scheme for telling the velocity of the Earth and the Solar System as a whole relative to the luminiferous ether, supposed at the time to be necessary for the propagation of electromagnetic waves. Maxwell's proposal to D. P. Todd, director of the Nautical Almanac office in Washington, D.C., was that accurate measurements of the rotation of Jupiter's satellites around their planet would allow this relative velocity through the ether to be derived. If Maxwell had been able to execute this plan (for which in Todd's opinion the data were not yet sufficiently accurate), he would have discovered that the ether is irrelevant to the propagation of electromagnetic waves and indeed does not exist—the foundation for Einstein's Theory of Special Relativity. 中

文

“On a Possible Mode of Detecting a Motion of the Solar System through the Luminiferous Ether”. By the late Prof. J. Clerk Maxwell. In a letter to Mr. D. P. Todd, Director of the *Nautical Almanac* Office, Washington, U. S. Communicated by Prof. Stoke, Sec. R. S. 中文

Mr. Todd has been so good as to communicate to me a copy of the subjoined letter, and has kindly permitted me to make any use of it.

中文

As the notice referred to by Maxwell in the *Encyclopaedia Britannica* is

very brief, being confined to a single sentence, and as the subject is one of great interest, I have thought it best to communicate the letter to the Royal Society. 中文

From the researches of Mr. Huggins on the radial component of the relative velocity of our sun and certain stars, the coefficient of the inequality which we might expect as not unlikely, would be only something comparable with half a second of time. This, no doubt, would be a very delicate matter to determine. Still, for anything we know *à priori* to the contrary, the motion might be very much greater than what would correspond to this; and the idea has a value of its own, irrespective of the possibility of actually making the determination. 中文

In his letter to me Mr. Todd remarks, "I regard the communication as one of extraordinary importance, although (as you will notice if you have access to the reply which I made) it is likely to be a long time before we shall have tables of the satellites of Jupiter sufficiently accurate to put the matter to a practical test." 中文

I have not thought it expedient to delay the publication of the letter on the chance that something bearing on the subject might be found among Maxwell's papers. 中文

(Copy)

Cavendish Laboratory,

Cambridge,

19th March, 1879

Sir,

I have received with much pleasure the tables of the satellites of Jupiter which you have been so kind as to send me, and I am

encouraged by your interest in the Jovial system to ask you if you have made any special study of the apparent retardation of the eclipses as affected by the geocentric position of Jupiter. [中文](#)

I am told that observations of this kind have been somewhat put out of fashion by other methods of determining quantities related to the velocity of light, but they afford the *only* method, so far as I know, of getting any estimate of the direction and magnitude of the velocity of the sun with respect to the luminiferous medium. Even if we were sure of the theory of aberration, we can only get differences of position of stars, and in the terrestrial methods of determining the velocity of light, the light comes back along the same path again, so that the velocity of the earth with respect to the ether would alter the time of the double passage by a quantity depending on the square of the ratio of the earth's velocity to that of light, and this is quite too small to be observed. [中文](#)

But if JE is the distance of Jupiter from the earth, and l the geocentric longitude, and if l' is the longitude and λ the latitude of the direction in which the sun is moving through ether with velocity v , and if V is the velocity of light and t the time of transit from J to E ,

$$JE = [V - v \cos \lambda \cos(l - l')]t$$

By a comparison of the values of t when Jupiter is in different signs of the zodiac, it would be possible to determine l' and $v \cos \lambda$. [中文](#)

I do not see how to determine λ , unless we had a planet with an orbit very much inclined to the ecliptic. It may be noticed that whereas the determination of V , the velocity of light, by this method depends on the differences of JE , that is, on the diameter of the earth's orbit, the determination of $v \cos \lambda$ depends on JE itself, a much larger quantity.

[中文](#)

But no method can be made available without good tables of the

motion of the satellites, and as I am not an astronomer, I do not know whether, in comparing the observations with the tables of Damoiseau, any attempt has been made to consider the term in $v \cos \lambda$. [中文](#)

I have, therefore, taken the liberty of writing to you, as the matter is beyond the reach of any one who has not made a special study of the satellites. [中文](#)

In the article E [ether] in the ninth edition of the “Encyclopaedia Britannica”, I have collected all the facts I know about the relative motion of the ether and the bodies which move in it, and have shown that nothing can be inferred about this relative motion from any phenomena hitherto observed, except the eclipses, &c., of the satellites of a planet, the more distant the better. [中文](#)

If you know of any work done in this direction, either by yourself or others, I should esteem it a favour to be told of it.

Believe me,

Yours faithfully,

(Signed) J. Clerk Maxwell [中文](#)

(21, 314-315; 1880)

麦克斯韦测量以太的计划

麦克斯韦最突出的科学成就之一是，他制定了地球和太阳系作为一个整体相对于以太的速度的测量计划。当时，以太被认为是电磁波传播的必要条件。麦克斯韦向华盛顿特区航海历书处的办公室主任托德建议，通过精确测量木星卫星围绕木星的公转可以得到太阳系整体相对于以太的速度。如果麦克斯韦当时真的实施了这个计划（托德认为该计划所需的数据还不够精确），那么他会发现，以太和电磁波的传播没有任何关系，而且实际上以太根本就不存在——这便是爱因斯坦的狭义相对论的基础。 [英文](#)

《论一种探测太阳系在以太中运动的可能方式》，作者是已故的克拉克·麦克斯韦教授。这篇文章出现在麦克斯韦写给美国华盛顿航海历书处的办公室主任托德先生的一封信中，由皇家学会的秘书斯托克教授宣读。 [英文](#)

托德先生十分慷慨地给了我一份附信的拷贝，并且大方地允许我使用它。 [英文](#)

因为麦克斯韦提到的《大英百科全书》中的参考资料十分简略，仅仅只有一句话。而这个题目又十分吸引人，所以我觉得最好还是在皇家学会宣读这封信。 [英文](#)

根据哈金斯先生对太阳和某些星体的相对速度径向分量的研究，系数上的差别（我们暂且认为结果可靠）大约只有半秒。毫无疑问，这对实验测量来说是一个很精细的问题。而且这和我们先验的观点相反，我们先验的观点中的运动比这里涉及到的大很多。如果不考虑实际测量的可操作性，这个想法还是有它自身的价值的。 [英文](#)

在托德先生给我的信中，他评论到，“虽然（如您将在我的答复中看

到的那样)将这个计划付诸实施需要足够精确的木星卫星的数据表,而且这恐怕需要很长时间才能获得,但是我仍然认为这封信极其重要。”

英文

将这封信推迟到可以在麦克斯韦的论文中找到相关内容的时候再发表,我认为并不适宜。 英文

(原信的拷贝)

卡文迪什实验室,

剑桥,

1879年3月19日

先生:

我非常高兴能收到您寄给我的木星卫星的数据表。受您对木星系统的兴趣的启发,我想问您有没有对由木星相对于地心的位置而造成的木星卫星蚀的明显延迟作过专门的研究。 英文

我得知,在其他测量与光速有关的物理量的方法面前,这种观测已经有些过时了。但是,据我所知,这种观测给我们提供了估算太阳相对于以太介质的速度的方向和大小的唯一方法。即便我们坚信像差理论,我们得到的也只是恒星位置的差别。并且按照在地球上测量光速的方法,光按原路返回,地球相对于以太的速度会改变这一往返的时间。但是,这个时间上的改变量依赖于地球速度与光速之比的平方,因此,这个量太小,以至于无法观测。 英文

但是,如果 J 表示木星与地球之间的距离, l 表示地心经度, l 和 λ 分别表示太阳在以太中运动方向的经度和纬度, v 表示太阳在以太中运动的速度, V 表示光速, t 表示光从木星到地球的传播时间,

$$JE = [V - v \cos \lambda \cos(l - l')]t$$

通过比较木星在黄道不同位置时的 t ,就有可能确定 l 和 $v \cos \lambda$ 。

英文

除非有一个行星的轨道向黄道极大倾斜，不然我就无法知道怎样确定 λ 。我们应该注意到，尽管用这种方法测量的光速 V 也与 $J-E$ 的变化有关，也就是说，依赖于地球轨道的直径，但是 $v \cos \lambda$ 却依赖于一个更大的量—— $J-E$ 本身。 [英文](#)

然而，没有精确的卫星运动数据就不会有任何行之有效的方法。我本人并不是天文学家，我不知道这些观测与达穆瓦索的数据表相比，是否曾经尝试过将 $v \cos \lambda$ 中的各项考虑在内。 [英文](#)

因此，我十分冒昧地给您写这封信。这个问题对没有专门研究过卫星的人来说，实在是勉为其难。 [英文](#)

在《大英百科全书》第9版关于以太的文章中，我收集了所有我知道的关于以太以及在其中运动的物体的相对运动的资料，从这些资料中我发现，由目前观测到的实验现象，除了行星离我们越远，越有利于卫星蚀等现象以外，从其他任何已观测到的相关现象中都不能推断出有关这种相对运动的结论。 [英文](#)

如果您知道有任何人，不论是您还是别人，做过这方面的工作，都请您告诉我，我将不胜感激。

相信我，

您忠实的，

（签名）克拉克·麦克斯韦 [英文](#)

（王静 翻译；鲍重光 审稿）

Clerk Maxwell's Scientific Work

P. G. Tait

James Clerk Maxwell died in November 1879. In this essay four months later, Scottish physicist Peter Guthrie Tait, who had known Maxwell from childhood, paid tribute to his accomplishments. Maxwell was producing influential, original work before the age of twenty. In 1864 he published a landmark paper giving the first complete statement of his theory of electricity and magnetism. It explained electromagnetic phenomena without recourse to action at a distance, and provided a unified view of what light is. Guthrie notes that the facility of Maxwell's thinking did not always translate into effective lectures. While the treatises he wrote were models of clarity, his extemporaneous lectures gave free rein to his imagination in a way that taxed his audiences. [中文](#)

AT the instance of Sir W. Thomson, Mr. Lockyer, and others I proceed to give an account of Clerk Maxwell's work, necessarily brief, but I hope sufficient to let even the non-mathematical reader see how very great were his contributions to modern science. I have the less hesitation in undertaking this work that I have been intimately acquainted with him since we were schoolboys together. [中文](#)

If the title of mathematician be restricted (as it too commonly is) to those who possess peculiarly ready mastery over symbols, whether they try to understand the significance of each step or no, Clerk

Maxwell was not, and certainly never attempted to be, in the foremost rank of mathematicians. He was slow in “writing out”, and avoided as far as he could the intricacies of analysis. He preferred always to have before him a geometrical or physical representation of the problem in which he was engaged, and to take all his steps with the aid of this: afterwards, when necessary, translating them into symbols. In the comparative paucity of symbols in many of his great papers, and in the way in which, when wanted, they seem to grow full-blown from pages of ordinary text, his writings resemble much those of Sir William Thomson, which in early life he had with great wisdom chosen as a model. 中文

There can be no doubt that in this habit, of constructing a mental representation of every problem, lay one of the chief secrets of his wonderful success as an investigator. To this were added an extraordinary power of penetration, and an altogether unusual amount of patient determination. The clearness of his mental vision was quite on a par with that of Faraday; and in this (the true) sense of the word he was a mathematician of the highest order. 中文

But the rapidity of his thinking, which he could not control, was such as to destroy, except for the very highest class of students, the value of his lectures. His books and his written addresses (always gone over twice in MS.) are models of clear and precise exposition; but his *extempore* lectures exhibited in a manner most aggravating to the listener the extraordinary fertility of his imagination. 中文

His original work was commenced at a very early age. His first printed paper, “*On the Description of Oval Curves, and those having a Plurality of Foci*”, was communicated for him by Prof. Forbes to the Royal Society of Edinburgh, and inserted in the “*Proceedings*” for 1846, before he reached his fifteenth year. He had then been taught only a book or two of Euclid, and the merest elements of Algebra. Closely connected with this are three unprinted papers, of which I have copies (taken in

the same year), on “*Descartes’ Ovals*”, “*The Meloid and Apioid*”, and “*Trifocal Curves*”. All of these, which are drawn up in strict geometrical form and divided into consecutive propositions, are devoted to the properties of plane curves whose equations are of the form

$$mr + nr' + pr'' + \dots = \text{constant}$$

$r, r', r'', \&c.$, being the distances of a point on the curve from given fixed points, and $m, n, p, \&c.$, mere numbers. Maxwell gives a perfectly general method of tracing all such curves by means of a flexible and inextensible cord. When there are but two terms, if m and n have the same sign we have the ordinary Descartes’ Ovals, if their signs be different we have what Maxwell called the Meloid and the Apioid. In each case a simple geometrical method is given for drawing a tangent at any point, and some of the other properties of the curves are elegantly treated. 中文

Clerk Maxwell spent the years 1847–1850 at the University of Edinburgh, without keeping the regular course for a degree. He was allowed to work during this period, without assistance or supervision, in the Laboratories of Natural Philosophy and of Chemistry: and he thus experimentally taught himself much which other men have to learn with great difficulty from lectures or books. His reading was very extensive. The records of the University Library show that he carried home for study, during these years, such books as Fourier’s *Théorie de la Chaleur*, Monge’s *Géometrie Descriptive*, Newton’s *Optics*, Willis’ *Principles of Mechanism*, Cauchy’s *Calcul Différentiel*, Taylor’s *Scientific Memoirs*, and others of a very high order. These were *read through*, not merely consulted. Unfortunately no list is kept of the books consulted in the Library. One result of this period of steady work consists in two elaborate papers, printed in the *Transactions of the Royal Society of Edinburgh*. The first (dated 1849) “*On the Theory of Rolling Curves*”, is a purely mathematical treatise, supplied with an

immense collection of very elegant particular examples. The second (1850) is “*On the Equilibrium of Elastic Solids*”. Considering the age of the writer at the time, this is one of the most remarkable of his investigations. Maxwell reproduces in it, by means of a special set of assumptions, the equations already given by Stokes. He applies them to a number of very interesting cases, such as the torsion of a cylinder, the formation of the large mirror of a reflecting telescope by means of a partial vacuum at the back of a glass plate, and the theory of Örsted’s apparatus for the compression of water. But he also applies his equations to the calculation of the strains produced in a transparent plate by applying couples to cylinders which pass through it at right angles, and the study (by polarised light) of the doubly-refracting structure thus produced. He expresses himself as unable to explain the permanence of this structure when once produced in isinglass, gutta percha, and other bodies. He recurred to the subject twenty years later, and in 1873 communicated to the Royal Society his very beautiful discovery of the *temporary* double refraction produced by shearing in viscous liquids. 中文

During his undergraduateship in Cambridge he developed the germs of his future great work on “Electricity and Magnetism” (1873) in the form of a paper “On Faraday’s Lines of Force”, which was ultimately printed in 1856 in the “Trans. of the Cam. Phil. Soc.” He showed me the MS. of the greater part of it in 1853. It is a paper of great interest in itself, but extremely important as indicating the first steps to such a splendid result. His idea of a fluid, incompressible and without mass, but subject to a species of friction in space, was confessedly adopted from the analogy pointed out by Thomson in 1843 between the steady flow of heat and the phenomena of statical electricity. 中文

Other five papers on the same subject were communicated by him to the *Philosophical Magazine* in 1861–1862, under the title *Physical Lines of Force*. Then in 1864 appeared his great paper “On a Dynamical

Theory of the Electromagnetic Field". This was inserted in the *Philosophical Transactions*, and may be looked upon as the first complete statement of the theory developed in the treatise on *Electricity and Magnetism*. [中文](#)

In recent years he came to the conclusion that such analogies as the conduction of heat, or the motion of the mass-less but incompressible fluid, depending as they do on Laplace's equation, were best symbolised by the quaternion notation with Hamilton's ∇ operator; and in consequence, in his work on electricity, he gives the expressions for all the more important physical quantities in their quaternion form, though without employing the calculus itself in their establishment. I have discussed in another place (*Nature*, vol. VII, p. 478) the various important discoveries in this remarkable work, which of itself is sufficient to secure for its author a foremost place among natural philosophers. I may here state that the main object of the work is to do away with "action at a distance," so far at least as electrical and magnetic forces are concerned, and to explain these by means of stresses and motions of the medium which is required to account for the phenomena of light. Maxwell has shown that, on this hypothesis, the velocity of light is the ratio of the electro-magnetic and electro-static units. Since this ratio, and the actual velocity of light, can be determined by absolutely independent experiments, the theory can be put at once to an exceedingly severe preliminary test. Neither quantity is yet fairly known within about 2 or 3 percent, and the most probable values of each certainly agree more closely than do the separate determinations of either. There can now be little doubt that Maxwell's theory of electrical phenomena rests upon foundations as secure as those of the undulatory theory of light. But the life-long work of its creator has left it still in its infancy, and it will probably require for its proper development the services of whole generations of mathematicians. [中文](#)

This was not the only work of importance to which he devoted the greater part of his time while an undergraduate at Cambridge. For he had barely obtained his degree before he read to the Cambridge Philosophical Society a remarkable paper *On the Transformation of Surfaces by Bending*, which appears in their *Transactions* with the date March 1854. The subject is one which had been elaborately treated by Gauss and other great mathematicians, but their methods left much to be desired from the point of view of simplicity. This Clerk Maxwell certainly supplied; and to such an extent that it is difficult to conceive that any subsequent investigator will be able to simplify the new mode of presentation as much as Maxwell simplified the old one. Many of his results, also, were real additions to the theory; especially his treatment of the *Lines of Bending*. But the whole matter is one which, except in its almost obvious elements, it is vain to attempt to popularise. 中文

The next in point of date of Maxwell's greatest works is his "Essay on the Stability of the Motion of Saturn's Rings", which obtained the Adam's Prize in the University of Cambridge in 1857. This admirable investigation was published as a pamphlet in 1859. Laplace had shown in the *Mécanique Céleste* that a uniform solid ring cannot revolve permanently about a planet; for, even if its density were so adjusted as to prevent its splitting, a slight disturbance would inevitably cause it to fall in. Maxwell begins by finding what amount of *want* of uniformity would make a solid ring stable. He finds that this could be effected by a satellite rigidly attached to the ring, and of about $4\frac{1}{2}$ times its mass:—but that such an arrangement, while not agreeing with observation, would require extreme artificiality of adjustment of a kind not elsewhere observed. Not only so, but the materials, in order to prevent its behaving almost like a liquid under the great forces to which it is exposed, must have an amount of rigidity far exceeding that of any known substance. 中文

He therefore dismisses the hypothesis of solid rings, and (commencing with that of a ring of equal and equidistant satellites) shows that a continuous liquid ring cannot be stable, but may become so when broken up into satellites. He traces in a masterly way the effects of the free and forced waves which must traverse the ring, under various assumptions as to its constitution; and he shows that the only system of rings which can dynamically exist must be composed of a very great number of separate masses, revolving round the planet with velocities depending on their distances from it. But even in this case the system of Saturn cannot be permanent, because of the mutual actions of the various rings. These mutual actions must lead to the gradual spreading out of the whole system, both inwards and outwards:—but if, as is probable, the outer ring is much denser than the inner ones, a very small increase of its external diameter would balance a large change in the inner rings. This is consistent with the progressive changes which have been observed since the discovery of the rings. An ingenious and simple mechanism is described, by which the motions of a ring composed of equal satellites can be easily demonstrated. [中文](#)

Another subject which he treated with great success, as well from the experimental as from the theoretical point of view, was the Perception of Colour, the Primary Colour Sensations, and the Nature of Colour Blindness. His earliest paper on these subjects bears date 1855, and the seventh has the date 1872. He received the Rumford Medal from the Royal Society in 1860, “For his Researches on the Composition of Colours and other optical papers”. Though a triplicity about colour had long been known or suspected, which Young had (most probably correctly) attributed to the existence of three sensations, and Brewster had erroneously* supposed to be objective, Maxwell was the first to make colour-sensation the subject of actual measurement. He proved experimentally that any colour C (given in intensity of illumination as well as in character) may be expressed in terms of three arbitrarily

chosen standard colours, X, Y, Z, by the formula

$$C = aX + bY + cZ$$

Here a , b , c are numerical coefficients, which may be positive or negative; the sign = means “matches”, + means “superposed”, and – directs the term to be taken to the other side of the equation. 中文

These researches of Maxwell’s are now so well known, in consequence especially of the amount of attention which has been called to the subject by Helmholtz’ great work on Physiological Optics, that we need not farther discuss them here. 中文

The last of his greatest investigations is the splendid Series on the Kinetic Theory of Gases, with the closely connected question of the sizes, and laws of mutual action, of the separate particles of bodies. The Kinetic Theory seems to have originated with D. Bernoulli; but his successors gradually reverted to statical theories of molecular attraction and repulsion, such as those of Boscovich. Herapath (in 1847) seems to have been the first to recall attention to the Kinetic Theory of gaseous pressure. Joule in 1848 calculated the average velocity of the particles of hydrogen and other gases. Krönig in 1856 (*Pogg. Ann.*) took up the question, but he does not seem to have advanced it farther than Joule had gone; except by the startling result that the weight of a mass of gas is only half that of its particles when at rest. 中文

Shortly afterwards (in 1859) Clausius took a great step in advance, explaining, by means of the kinetic theory, the relations between the volume, temperature and pressure of a gas, its cooling by expansion, and the slowness of diffusion and conduction of heat in gases. He also investigated the relation between the length of the mean free path of a particle, the number of particles in a given space, and their least distance when in collision. The special merit of Clausius’ work lies in his introduction of the processes of the theory of probabilities into the

treatment of this question.

中文

Then came Clerk Maxwell. His first papers are entitled “Illustrations of the Dynamical Theory of Gases”, and appeared in the *Phil. Mag.* in 1860. By very simple processes he treats the collisions of a number of perfectly elastic spheres, first when all are of the same mass, secondly when there is a mixture of groups of different masses. He thus verifies Gay-Lussac’s law, that the number of particles per unit volume is the same in all gases at the same pressure and temperature. He explains gaseous friction by the transference to and fro of particles between contiguous strata of gas sliding over one another, and shows that the coefficient of viscosity is independent of the density of the gas. From Stokes’ calculation of that coefficient he gave the first deduced approximate value of the mean length of the free path; which could not, for want of data, be obtained from the relation given by Clausius. He obtained a closely accordant value of the same quantity by comparing his results for the kinetic theory of diffusion with those of one of Graham’s experiments. He also gives an estimate of the conducting power of air for heat; and he shows that the assumption of non-spherical particles, which during collision change part of their energy of translation into energy of rotation, is inconsistent with the known ratio of the two specific heats of air. 中文

A few years later he made a series of valuable experimental determinations of the viscosity of air and other gases at different temperatures. These are described in *Phil. Trans.* 1866; and they led to his publishing (in the next volume) a modified theory, in which the gaseous particles are no longer regarded as perfectly elastic, but as repelling one another according to the law of the inverse fifth power of the distance. This paper contains some very powerful analysis, which enabled him to simplify the mathematical theory for many of its most important applications. Three specially important results are given in conclusion, and they are shown to be independent of the

particular mode in which gaseous particles are supposed to act on one another. These are:—

1. In a mixture of particles of two kinds differing in amounts of mass, the average energy of translation of a particle must be the same for either kind. This is Gay Lussac's Law already referred to.
2. In a vertical column of mixed-gases, the density of each gas at any point is ultimately the same as if no other gas were present. This law was laid down by Dalton.
3. Throughout a vertical column of gas gravity has no effect in making one part hotter or colder than another; whence (by the dynamical theory of heat) the same must be true for all substances. [中文](#)

Maxwell has published in later years several additional papers on the Kinetic Theory, generally of a more abstruse character than the majority of those just described. His two latest papers (in the *Phil. Trans.* and *Camb. Phil. Trans.* of last year) are on this subject:—one is an extension and simplification of some of Boltzmann's valuable additions to the Kinetic Theory. The other is devoted to the explanation of the motion of the radiometer by means of this theory. Several years ago (*Nature*, vol. XII, p. 217), Prof. Dewar and the writer pointed out, and demonstrated experimentally, that the action of Mr. Crookes' very beautiful instrument was to be explained by taking account of the increased length of the mean free path in rarefied gases, while the then received opinions ascribed it either to evaporation or to a quasi-corpuscular theory of radiation. Stokes extended the explanation to the behaviour of disks with concave and convex surfaces, but the subject was not at all fully investigated from the theoretical point of view till Maxwell took it up. During the last ten years of his life he had no rival to claim concurrence with him in the whole wide domain of molecular forces, and but two or three in

the still more recondite subject of electricity. 中文

“Every one must have observed that when a slip of paper falls through the air, its motion, though undecided and wavering at first, sometimes becomes regular. Its general path is not in the vertical direction, but inclined to it at an angle which remains nearly constant, and its fluttering appearance will be found to be due to a rapid rotation round a horizontal axis. The direction of deviation from the vertical depends on the direction of rotation...These effects are commonly attributed to some accidental peculiarity in the form of the paper...” So writes Maxwell in the *Cam. and Dub. Math. Jour.* (May, 1854), and proceeds to give an exceedingly simple and beautiful explanation of the phenomenon. The explanation is, of course, of a very general character, for the complete working out of such a problem appears to be, even yet, hopeless; but it is thoroughly characteristic of the man, that his mind could never bear to pass by any phenomenon without satisfying itself of at least its general nature and causes. 中文

In the same volume of the *Math. Journal* there is an exceedingly elegant “problem” due to Maxwell, with his solution of it. In a note we are told that it was “suggested by the contemplation of the structure of the crystalline lens in fish”. It is as follows:— 中文

A transparent medium is such that the path of a ray of light within it is a given circle, the index of refraction being a function of the distance from a given point in the plane of the circle. Find the form of this function, and show that for light of the same refrangibility—

1. The path of *every ray within the medium* is a circle.
2. All the rays proceeding from any point in the medium will meet accurately in another point.
3. If rays diverge from a point without the medium and enter it through a spherical surface having that point for its centre, they will be made to converge accurately to a point within the

medium. [中文](#)

Analytical treatment of this and connected questions, by a novel method, will be found in a paper by the present writer (*Trans. R. S. E.* 1865). [中文](#)

Optics was one of Clerk Maxwell's favourite subjects, but of his many papers on various branches of it, or subjects directly connected with it, we need mention only the following:—

“On the General Laws of Optical Instruments” (*Quart. Math. Jour.* 1858)

“On the Cyclide” (*Quart. Math. Journal*, 1868)

“On the best Arrangement for Producing a Pure Spectrum on a Screen” (*Proc. R. S. E.* 1868)

“On the Focal Lines of a Refracted Pencil” (*Math. Soc. Proc.* 1873)

[中文](#)

A remarkable paper, for which he obtained the Keith Prize of the *Royal Society of Edinburgh*, is entitled “On Reciprocal Figures, Frames, and Diagrams of Forces.” It is published in the *Transactions* of the Society for 1870. Portions of it had previously appeared in the *Phil. Mag.* (1864). [中文](#)

The triangle and the polygon of forces, as well as the funicular polygon, had long been known; and also some corresponding elementary theorems connected with hydrostatic pressure on the faces of a polyhedron; but it is to Rankine that we owe the full principle of diagrams, and reciprocal diagrams, of frames and of forces. Maxwell has greatly simplified and extended Rankine's ideas: on the one hand facilitating their application to practical problems of construction, and on the other hand extending the principle to the general subject of stress in bodies. The paper concludes with a valuable extension to three dimensions of Sir George Airy's “Function of Stress”. [中文](#)

His contributions to the *Proceedings of the London Mathematical Society* were numerous and valuable. I select as a typical specimen his paper on the forms of the stream-lines when a circular cylinder is moved in a straight line, perpendicular to its axis, through an infinitely extended, frictionless, incompressible fluid (vol. III, p. 224). He gives the complete solution of the problem; and, with his usual graphical skill, so prominent in his great work on Electricity, gives diagrams of the stream-lines, and of the paths of individual particles of the fluid. The results are both interesting and instructive in the highest degree.

中文

In addition to those we have mentioned we cannot recall many pieces of *experimental* work on Maxwell's part:—with two grand exceptions. The first was connected with the determination of the British Association Unit of Electric Resistance, and the closely associated measurement of the ratio of the electrokinetic to the electrostatic unit. In this he was associated with Professors Balfour Stewart and Jenkin. The Reports of that Committee are among the most valuable physical papers of the age; and are now obtainable in a book-form, separately published. The second was the experimental verification of Ohm's law to an exceedingly close approximation, which was made by him at the Cavendish Laboratory with the assistance of Prof. Chrystal. 中文

In his undergraduate days he made an experiment which, though to a certain extent physiological, was closely connected with physics. Its object was to determine why a cat always lands on its feet, however it may be let fall. He satisfied himself, by pitching a cat gently on a mattress stretched on the floor, giving it different initial amounts of rotation, that it instinctively made use of the conservation of Moment of Momentum, by stretching out its body if it were rotating so fast as otherwise to fall head foremost, and by drawing itself together if it were rotating too slowly. 中文

I have given in this journal (vol. XVI, p. 119) a detailed account of his

remarkable elementary treatise on “Matter and Motion”, a work full of most valuable materials, and worthy of most attentive perusal not merely by students but by the foremost of scientific men. 中文

His “Theory of Heat”, which has already gone through several editions, is professedly elementary, but in many places is probably, in spite of its admirable definiteness, more difficult to follow than any other of his writings. In intrinsic importance it is of the same high order as his “Electricity”, but as a whole it is *not* an elementary book. One of the few knowable things which Clerk Maxwell did not know, was the distinction which most men readily perceive between what is easy and what is hard. What *he called* hard, others would be inclined to call altogether unintelligible. In the little book we are discussing there is matter enough to fill two or three large volumes without undue dilution (perhaps we should rather say, *with the necessary dilution*) of its varied contents. There is nothing flabby, so to speak, about anything Maxwell ever wrote: there is splendid muscle throughout, and an adequate bony structure to support it. “Strong meat for grown men” was one of his favourite expressions of commendation; and no man ever more happily exposed the true nature of the so-called “popular science” of modern times than he did when he wrote of “the forcible language and striking illustrations by which those who are past hope of being even beginners [in science] are prevented from becoming conscious of intellectual exhaustion before the hour has elapsed.” 中文

To the long list of works attached to Maxwell’s name in the Royal Society’s Catalogue of Scientific Papers may now be added his numerous contributions to the latest edition of the “Encyclopaedia Britannica”—Atom, Attraction, Capillarity, &c. Also the laborious task of preparing for the press, with copious and very valuable original notes, the “Electrical Researches of the Hon. Henry Cavendish.” This work has appeared only within a month or two, and contains many

singular and most unexpected revelations as to the early progress of the science of electricity. We hope shortly to give an account of it.

中文

The works which we have mentioned would of themselves indicate extraordinary activity on the part of their author, but they form only a fragment of what he has published; and when we add to this the further statement, that Maxwell was always ready to assist those who sought advice or instruction from him, and that he has read over the proof-sheets of many works by his more intimate friends (enriching them by notes, always valuable and often of the quaintest character), we may well wonder how he found time to do so much. 中文

Many of our readers must remember with pleasure the occasional appearance in our columns of remarkably pointed and epigrammatic verses, usually dealing with scientific subjects, and signed $\frac{dp}{dt}$ †. The lines on Cayley's portrait, where determinants, roots of -1 , space of n dimensions, the 27 lines on a cubic surface, &c., fall quite naturally into rhythmical English verse; the admirable synopsis of Dr. Ball's Treatise on Screws; the telegraphic love-letter with its strangely well-fitting *volts* and *ohms*; and specially the "Lecture to a Lady on Thomson's Reflecting Galvanometer", cannot fail to be remembered. No living man has shown a greater power of condensing the whole marrow of a question into a few clear and compact sentences than Maxwell shows in these verses. Always having a definite object, they often veiled the keenest satire under an air of charming innocence and naïve admiration. Here are a couple of stanzas from unpublished pieces of a similar kind:—first, some ghastly thoughts by an excited evolutionist—

To follow my thoughts as they go on,
Electrodes I'd place in my brain;
Nay, I'd swallow a live entozöon,
New feelings of life to obtain—

next on the non-objectivity of Force—

Both Action and Reaction now are gone;
Just ere they vanished
Stress joined their hands in peace, and made them one,
Then they were banished. 中文

It is to be hoped that these scattered gems may be collected and published, for they are of the very highest interest, as the work during leisure hours of one of the most piercing intellects of modern times. Every one of them contains evidence of close and accurate thought, and many are in the happiest form of epigram. 中文

I cannot adequately express in words the extent of the loss which his early death has inflicted not merely on his personal friends, on the University of Cambridge, on the whole scientific world, but also, and most especially, on the cause of common sense, of true science, and of religion itself, in these days of much vain-babbling, pseudo-science, and materialism. But men of his stamp never live in vain; and in one sense at least they cannot die. The spirit of Clerk Maxwell still lives with us in his imperishable writings, and will speak to the next generation by the lips of those who have caught inspiration from his teachings and example. 中文

(21, 317-321; 1880)

* All we can positively say to be erroneous is some of the principal arguments by which Brewster's view was maintained, for the subjective character of the triplicity has not been absolutely *demonstrated*.

† This *nom de plume* was suggested to him by me from the occurrence of his initials in the well-known expression of the second Law of Thermodynamics (for whose establishment on thoroughly valid grounds he did so much) $\frac{dp}{dt} = J. C. M.$

克拉克·麦克斯韦的科学工作

泰特

1879年11月，詹姆斯·克拉克·麦克斯韦逝世。在4个月后的这篇短文中，苏格兰物理学家彼得·格思里·泰特（他从小就认识麦克斯韦）热情称颂了麦克斯韦的成就。麦克斯韦在20岁之前就开始发表有影响力的原创研究论文。1864年，他发表了一篇首次完整阐述其电磁理论的论文。在这篇里程碑式的论文中，麦克斯韦抛开一定距离外的实际效应去解释电磁现象，并就光的本质提出了一个统一性的观点。格思里认为，麦克斯韦深刻的思考并没有通过他那些颇有影响的演讲全部体现出来。不过，与他那堪称逻辑清晰之典范的专著不同，他的即席演讲在某种程度上则更自由地展现了他那对听众来说过于跳跃的想象力。 [英文](#)

应汤姆孙爵士、洛克耶先生以及其他一些人士的要求，我将对麦克斯韦的科学工作进行介绍。介绍必然是简略的，但我希望足以让即使没有数学背景的读者也能了解他对现代科学的伟大贡献。我与麦克斯韦在学生时代就已经熟识，因此，我毫不犹豫地接受了这个任务。 [英文](#)

如果说数学家的头衔只属于那些不论是否试图理解每一步的意义，都对符号了如指掌的人（事实通常就是这样），那么克拉克·麦克斯韦就不是、也从来不试图成为这样的一流数学家。他总是不慌不忙地“完稿”，并且尽可能避免复杂的分析。他更喜欢以几何或物理的形式表示自己所研究的问题，并且总是借助于以下方式来完成下一步的研究：在必要时，将这些表示转化成符号的形式。在他众多的伟大著作中所出现的较少的符号，在需要的时候似乎又能拓展成为直接触及主题的成熟的篇章，从这些方面来看，他的著作与威廉·汤姆孙爵士的十分相似，他在早年就很有远见卓识地把爵士当作自己的榜样。 [英文](#)

毫无疑问，为每个问题建立思维上的表示，这个习惯是麦克斯韦作为一名研究者能够获得巨大成功的主要秘诀之一。除此之外，他还拥有卓越的洞察力和非凡的意志力。他的思路清晰，堪比法拉第。从数学家一词的这种（真正的）意义来说，麦克斯韦就是一位最高层次的数学家。 [英文](#)

然而，麦克斯韦的思维之敏捷，连他自己都无法控制，这使得他的讲座只能被极高层次的学生所接受，而其他人士则很难从中受益。他的著作和演讲稿（通常是对手稿的再一次重温）是表述清晰精确的典范；但是他的即席演讲却因为极富想象力的风格而使听众难以理解。 [英文](#)

麦克斯韦最初的工作在他年轻时就已着手展开。他发表的第一篇论文《论椭圆曲线及多焦点椭圆曲线》由福布斯教授代他在爱丁堡皇家学会的会议上宣读，并收录在《爱丁堡皇家学会会刊》中。当时是1846年，麦克斯韦尚不满15岁。那时的他只学过一两本欧几里德的书和最基本的代数基础。紧接着，他又写了另外3篇没有发表的文章，我有这几篇文章的拷贝，它们分别是：《笛卡尔椭圆》《茺菁科昆虫形曲线和芹亚科植物形曲线》《三焦点曲线》。这些建立在严格的几何形式上并且被分成论题连贯的文章，可以用来研究具有以下形式的方程所描述的平面曲线的性质：

$$mr + nr' + pr'' + \dots = \text{常量}$$

r, r', r'' 等是从一个给定的固定点到曲线上某一点的距离， m, n, p 等仅仅是一些数字。麦克斯韦用容易弯曲但不能伸展的绳子，给出了一种理想的绘制这样曲线的一般方法。当方程中只有 m 和 n 两项时，如果两者同号，就得到普通的笛卡尔椭圆，如果两者异号，就得到麦克斯韦所谓的茺菁科昆虫形曲线和芹亚科植物形曲线。在每种情况下，麦克斯韦都给出了在任意一点作切线的简单几何方法，并且很好地处理了曲线其他方面的性质。 [英文](#)

1847~1850年，克拉克·麦克斯韦就读于爱丁堡大学，在此他并不需要去学那些学位要求的常规课程，而是被允许在既无人帮助也无人指导的条件下在自然哲学与化学实验室工作。因此，他在实验中自学了很

多东西，而这些是其他人很难从书本中或课堂上学到的。他的阅读非常广泛。大学图书馆的记录显示，他在这些年中借回家研读的书有傅立叶的《热力学理论》、蒙日的《几何学说明》、牛顿的《光学》、威利斯的《力学原理》、柯西的《微分计算》、泰勒的《科学回忆录》等高水平著作。这些书他全部通读，而不是仅仅翻阅一下。很可惜图书馆没有保存他在馆内阅览的书单。麦克斯韦这段时间持续学习的成果之一是发表在《爱丁堡皇家学会会报》上的两篇详细论文。第一篇《论曲线滚动理论》（1849年），这是一篇纯数学的论文，文章给出了大量简洁而恰当的例子。第二篇是《论弹性固体的平衡》（1850年）。考虑到作者当时的年龄，这可以被认为是他最不寻常的研究之一。麦克斯韦运用一系列特殊的假设，重新构造了已经由斯托克斯给出的方程。他将这些方程应用到许多非常有趣的情况中，比如圆柱体的扭曲、通过在玻璃板后形成局部真空的方法实现反射式望远镜的巨大镜面的构造、奥斯特的水压缩装置的理论。此外，他还将其方程应用于张力（向一个垂直穿过透明板的圆柱体施加力偶后在透明平板中产生的）的计算，以及对同样产生的双折射结构的研究（用偏振光）。他无法解释为什么在云母、杜仲胶以及其他物体中一旦产生了这种结构就会持续存在。20年以后，他又重新回到这个题目，并于1873年向皇家学会宣读了他非常美妙的发现——由粘性液体中的切变造成的暂时双折射。 [英文](#)

在剑桥读本科时，麦克斯韦完成了最终于1856年发表在《剑桥哲学学会学报》上的论文《论法拉第力线》，这篇文章是他后来的伟大著作《电磁学》（1873年）的雏形。1853年，他曾给我看过这篇论文的大部分手稿。这篇论文本身就十分有趣，但更重要的是它显示了走向未来辉煌成就的第一步。麦克斯韦关于流体的观点是，流体不可压缩，没有质量，但是要克服空间中的某种摩擦力，这无疑采用了汤姆孙于1843年从稳定热流和静电现象之间类推出的结果。 [英文](#)

关于这个主题还有另外5篇文章，以《论物理力线》为题发表在1861~1862年间的《哲学杂志》上。1864年，他的伟大著作《电磁场的动力学理论》问世了。这篇文章被收录在《自然科学会报》上，可以将其看作对《电磁学》专著中所阐述理论的第一次完整论述。 [英文](#)

近年，他得出了以下结论：对于这些遵循拉普拉斯方程的类似物理

量，比如热传导或没有质量却不可压缩的流体运动来说，含有哈密顿算子 ∇ 的四维表示法是最佳的表示方式。接着，他在电学研究中给出了所有更重要的物理量的四维形式，然而他并没有在建立表示方法的同时进行计算。我在别处（《自然》，第7卷，第478页）讨论过这项伟大工作中的多个重要发现，这本身就足以使其作者跻身最伟大的科学家行列。我可以在这里说，这项工作的目标就是，至少在涉及电磁力时，弄清“超距作用”，并且要通过光现象所需的介质应力和运动来解释它们。麦克斯韦指出，在这种假设下，光速为电磁单元与静电单元之比。因为这个比值和光速都可以由完全独立的实验确定，所以上面的理论可以用极为严格的初级实验来检验。但是，目前这两个物理量都还没能在2%~3%的误差范围内被清楚地认识，每个量的最可几数值当然比分散的数值更加集中。现在毫无疑问，麦克斯韦电现象理论建立的基础和光的波动学说的基础一样可信。但是，这个理论在其创建者的毕生努力下也还是处在初级阶段，它的合理发展可能还需要整整一代数学家的努力。 [英文](#)

以上并不是麦克斯韦利用在剑桥读本科期间的大部分时间来完成的唯一重要的工作。因为直到他在剑桥哲学学会的会议上宣读了一篇著名的论文《论弯曲引起的表面变换》，并于1854年3月发表在《剑桥哲学学会学报》上，他才获得了学位。高斯和其他一些伟大的数学家都曾经详细研究过这个课题，但是从简洁的角度来看，他们的方法还有很多需要改进的地方。克拉克·麦克斯韦无疑完成了后续的简化工作，并且将其简化到了这样的程度：很难想象任何一个后继研究者在简化现有的新模型时，能达到像麦克斯韦简化旧模型时那样的程度。他的很多结果，是对原有理论的丰富，尤其是他对弯曲线所作的处理。但问题是，除了其中几乎显而易见的部分，这些结果都没有实现普及。 [英文](#)

麦克斯韦的下一个伟大著作是《关于土星环运动稳定性的评论》，这篇文章在1857年获得了剑桥大学的亚当斯奖。这项令人称赞的研究在1859年被印成了小册子。拉普拉斯在他的《天体力学》中指出，均匀的固体环不可能持久地围绕行星转动，因为，即使环的密度调整到可以使其避免分裂的程度，一个微小的扰动也会不可避免地导致其塌陷。麦克斯韦从寻找使一个固体环稳定所需的均匀度开始。他发现，可以通过将一个卫星与这个环作刚性连接来实现环的稳定，其中卫星的质量等于环

质量的 $4\frac{1}{2}$ 倍。但是由于这种方法与观测不符，于是就需要极精巧的调节方式，而这种调节方式也没有在其他地方看到过。不但如此，为了避免环出现类似暴露在强力下的液体那样的表现，环的材料必须具有足够的硬度，而这种硬度远远超过了任何已知材料的硬度。 [英文](#)

因此，麦克斯韦放弃了固体环的假设，开始设想一个由等距的相同行星组成的环。他指出，连续的液体环无法保持稳定，但是当它破裂成多个卫星的时候就可能达到稳定状态。他极为巧妙地论述了在各种假设的环结构中必须穿过环的或自由或受迫的波的影响，并且指出，唯一一种能够动态稳定存在的环形结构必须由大量分离的物质组成，这些物质围绕行星转动，其速度取决于它们到行星的距离。然而，即使在这种情况下，由于不同环之间的相互作用，土星系统也不可能持久稳定。因为这种相互作用必然会导致整个系统向内外两个方向扩散。但是，如果外环密度比内环密度大，外环直径很小的增大就能平衡内环直径很大的改变。这与环被发现以来所观察到的不断变化是一致的。麦克斯韦描述了一个独特而又简洁的机制，用它可以很容易地说明由相同卫星组成的环的运动。 [英文](#)

麦克斯韦的另一个研究课题是颜色的感知、基础色觉以及色盲的本质。这项工作无论是从实验角度还是从理论角度来看都极为成功。他最早关于这些问题的文章诞生于1855年，第7篇则发表于1872年。“由于他在颜色组成方面的研究和其他光学方面的论文”，麦克斯韦在1860年获得了皇家学会颁发的拉姆福德奖章。虽然人们知道或者猜测出颜色的三原色已经有很长一段时间了，例如杨曾经（很可能正确地）把三原色归因于存在三种主观色觉，而布鲁斯特错误地猜测三原色是客观的，但是麦克斯韦却是第一个将实际测量引入色觉这个课题的人。他在实验中证明了，任何颜色C（以照度和特性的形式给出）都可以用三种任选的标准颜色X，Y，Z按照下面的公式表示出来：

$$C = aX + bY + cZ$$

其中， a ， b ， c 是数值系数，可以取正也可以取负；等号表示“匹配”，加号表示“叠加”，减号表示把这一项移到方程的另一边。 [英文](#)

现在麦克斯韦的这些研究已经是众所周知的了，特别是后来亥姆霍

兹关于生理光学的伟大工作使得这个研究课题吸引了很多注意力，因此，我们就不需要在这里进一步详细讨论它们了。 [英文](#)

麦克斯韦最后一项伟大的研究是他那套卓越的关于气体动力学的丛书。这套丛书的内容与物体离散粒子的大小和相互作用定律等问题密切相关。动力学理论似乎最早起源于伯努利，但是他的后继者逐渐回归到关于粒子吸引和排斥的统计理论上，就如博斯科维克所做的那样。赫拉帕斯（1847年）似乎是第一个重新注意到气体压力动力学理论的人。焦耳在1848年计算了氢气和其他气体微粒的平均速度。科隆尼格在1856年（《波根多夫年鉴》）考虑到了这个问题，但是除了得到气体的重量只有静止气体微粒的一半这一惊人结果之外，他似乎并没有进一步发展焦耳的结果。 [英文](#)

在不久之后（1859年），克劳修斯取得了巨大的进展。他用动力学理论成功地解释了气体体积、温度、压强之间的关系，膨胀造成的冷却，以及气体中缓慢的热扩散和热传导。他还研究了气体微粒的平均自由程长度、给定空间中的粒子数以及粒子碰撞过程中的最小距离这三者之间的关系。克劳修斯工作的最大价值在于，他在处理这个问题时，引入了概率论的方法。 [英文](#)

然后就是克拉克·麦克斯韦。他第一篇论文的题目是《气体动力学理论图示》，于1860年发表在《哲学杂志》上。他通过一个非常简单的过程来处理许多完全弹性小球的碰撞。他首先研究了所有小球的质量都相等的情况，然后研究了含有不同质量小球的情况。他由此证明了盖·吕萨克定律，即在同温同压下，所有气体单位体积内的粒子数相等。他把气体的摩擦力解释为相邻气层之间微粒的相对运动，并且指出粘滞系数和气体的密度无关。他从斯托克斯对粘滞系数的计算出发，第一次推出了气体平均自由程的近似值，由于缺少数据，这个数值是无法从克劳修斯给出的关系中得到的。他把自己用扩散动力学理论计算出的结果和格雷厄姆一个实验的结果进行比较，发现二者能够很好地吻合。麦克斯韦还估算出了空气的热导率，并且指出，非球形粒子在碰撞中能将部分平动动能转化为转动动能的假设与已知的空气的两种比热之比不符。 [英文](#)

几年后，他做了一系列很有价值的实验，来确定不同温度下空气和其他气体的粘性。这些工作的结果发表在1866年的《自然科学会报》上。在该杂志接下来的一卷上，他又发表了修正后的理论，此理论中不再把气体粒子视为完全弹性小球，而是认为粒子之间存在着与相互距离的五次方成反比的排斥作用。这篇论文包含一些非常有力的分析，这使得他可以为理论的重要应用而进行数学理论上的简化。结论中给出了3个特别重要的结果，并且这些结果和气体粒子之间的相互作用模型无关。它们是：

1. 在由两种质量不同的粒子组成的混合物中，两种粒子的平均平动动能一定相等。这是盖·吕萨克定律已经提到过的。
2. 在装有混合气体的立柱容器中，每一种气体在任一点的密度最终都将相同，就好像没有其他气体存在一样。这个定律是道尔顿建立的。
3. 在整个装有气体的立柱容器中，重力并没有使某一部分的温度高于或低于另外一部分。因此（根据热动力学理论），这个规律应该适用于所有物质。

[英文](#)

在之后的几年中，麦克斯韦发表了另外几篇关于动力学理论的文章，这些文章比上面提到的工作中的大多数都更加深奥。他最近的两篇论文发表在去年的《自然科学会报》和《剑桥哲学学报》上：一篇是对玻耳兹曼在动力学理论上的重要补充的推广和简化；另一篇文章中，他用这个理论解释了辐射计的运转。几年之后，杜瓦教授等人（《自然》，第12卷，第217页）指出并且通过实验证实了：考虑到稀薄气体中平均自由程的增加，无论是采用蒸气辐射理论还是准颗粒辐射理论都可以解释克鲁克斯先生非常精巧的仪器的作用。斯托克斯将其推广，用于解释具有凹凸表面的圆盘的行为，但是从理论的角度来看，这个课题在麦克斯韦着手之前并没有得到充分的研究。在麦克斯韦生命的最后十年里，他没有遇到能够在分子力学的广阔领域内和他平起平坐的对手，然而在更深奥的电学领域，倒是有两三个人能与他相提并论。

[英文](#)

“每个人都会注意到，一张纸片在空气中飘落时，虽然一开始摇摆不定，但是它的运动会趋于规则。它通常的路径并不是沿垂直方向，而是与垂直方向成一个角度，这个角度基本是一个常数。我们会发现纸片一

开始的飘动是围绕一条水平轴快速转动。偏离垂直轴的方向取决于转动的方向……。这些结果通常被归因于纸张形状的某些偶然特性……”麦克斯韦在1854年5月发表于《剑桥与都柏林数学杂志》上的文章中这样写到，他想对这个现象作出非常简洁而漂亮的解释。当然，这个解释十分笼统，因为即使现在看来，完全解决这个问题也是希望渺茫。但这正是麦克斯韦的性格，他的思想决不容忍自己与任何连一般性质及成因都得不到满意解释的现象擦肩而过。 [英文](#)

在《剑桥与都柏林数学杂志》的同一卷中，麦克斯韦提出了一个极其精彩的“问题”，并且自己作出了解答。我们从一则记录中得知，这个工作是“在思考鱼的晶状体结构时受到的启发”。内容如下： [英文](#)

所谓介质是透明的就是指光线在此介质中的传播路径是一个特定的圆，介质某一点的折射率是这一点到圆平面中给定点距离的函数。我找到了这个函数的形式，并且发现对于具有相同折射性质的光线来说——

1. 每一条光线在介质中的路径都是一个圆。
2. 从介质中任意一点发出的光线，都会在另外一点精确相遇。
3. 如果光线在介质外的某一点发散，并且经由一个以此发散点为球心的球面进入介质，那么这些光线将精确地会聚到介质中的某一点上。 [英文](#)

我本人在一篇文章（《爱丁堡皇家学会会报》，1865年）中，用一种新颖的方法对这个问题及相关问题进行了分析。 [英文](#)

光学是克拉克·麦克斯韦最喜欢的课题之一，但是在他关于光学不同分支或者直接与光学相关的大量文章中，我们只需提及下面这些：

《论光学仪器的普遍规律》（《数学季刊》，1858年）

《论四次圆纹曲面》（《数学季刊》，1868年）

《论在屏幕上生成纯光谱的最佳方案》（《爱丁堡皇家学会会刊》，1868年）

《论折射光束的焦线》（《数学学会会刊》，1873年） [英文](#)

麦克斯韦还有一篇意义重大的文章，题目是《论力的对应线图、框架和图解》，为此他获得了爱丁堡皇家学会的基思奖。文章于1870年发表在《爱丁堡皇家学会会报》上，文章中的一部分之前已经在《哲学杂志》（1864年）上出现过。 [英文](#)

力的三角法则、多边形法则、以及索状多边形法则早已为人们所熟知，一些和多面体表面静压有关的基础理论也是如此。但是兰金认为，我们缺少一套关于力的线图、框架、图解以及力本身的完整法则。麦克斯韦极大地简化并推广了兰金的观点：一方面，他使这个理论在建筑学实际问题上的应用更加方便；另一方面，他将这个理论推广到了物体中的压力这一般主体。在文章结尾，麦克斯韦将乔治·艾里爵士的“压力函数”推广到了三维的情形，这个推广很有意义。 [英文](#)

他为《伦敦数学学会会刊》贡献了大量有价值的稿件。我选取他的一篇文章作为其中的典范。这篇文章讨论了当一个圆柱体沿着垂直于轴的直线穿过一个不可压缩、无摩擦且可无限扩展的液体时液体中流线的形式（第3卷，第224页）。他给出了这个问题的完整解答，并且利用他在电学巨著中常用的图解技巧给出了流线和液体中单个粒子路径的图形。 [英文](#)

除了上面提到的那些工作，麦克斯韦没有多少实验性的工作能被我们铭记，但是有两个工作是例外。第一个是关于确定电阻英制单位以及与其密切相关的电动力学单位与静电学单位之比的测量。这个工作是麦克斯韦和鲍尔弗·斯图尔特教授、詹金教授合作完成的。相关委员会的报告是这个时期最有价值的物理学论文之一，现在这些报告已经集结成册并且单独出版了。第二项工作是在实验上以极高的精度验证了欧姆定律。这项工作是在卡文迪什实验室由克里斯托尔教授协助完成的。

[英文](#)

麦克斯韦在读本科期间做了一个实验，虽然从某种程度上说这是一个生理学实验，但是它也和物理学密切相关。实验的目的是解释为什么猫在落地的时候总是能保持脚先着地。实验中他把猫轻轻地抛到毯子上，抛掷时，让猫具有不同的初始转动。麦克斯韦得到了满意的结果：猫在空中的时候，本能地利用了角动量守恒。如果给它的初始转动过

快，它就会把身体伸展开，避免头先着地；相反地，如果给它的初始转动过慢，它就会缩成一团，最后总是能避免头先着地。 [英文](#)

我曾经在贵刊上（第16卷，第119页）详细介绍了麦克斯韦著名的关于《物质和运动》的基础论文。他的这项工作有许多重要的结果，因此值得每一个人——不仅仅是学生，还包括一流的科学家——仔细阅读。 [英文](#)

他的《热学理论》已经出了好几版。尽管他自称这部书很基础，尽管书的思路的确非常清晰，但是其中许多地方可能比作者的其他任何著作都更难理解。这部书本身的重要性堪比他的《电学》，但是总体上却不是一本基础读物。克拉克·麦克斯韦不知道的少数几个显而易见的事情之一就是，难与易的区别，而这是多数人都能分清的。他所谓的难事，其他人会认为是根本无法理解的。我们正在谈论的这本薄薄的书的内容不用过度展开（可能我们应该说，经过必要的展开），其内容就足以写满两三卷书。可以说，麦克斯韦写的东西从不松散拖沓：他的文章只有健美的肌肉和适量的用以支撑的骨架。“成人的强健肌肉”是麦克斯韦最喜欢的表达称赞的说法。“过来人总是希望自己保持那种〔科学上的〕初学者的状态，对他们来说，有力的语言和精彩的图示就是能在时间消逝之前避免灵感和智慧枯竭的灵药。”当麦克斯韦写出上面这段话时，恐怕没有人比他更乐于揭示现代所谓“流行科学”的真实本质了。 [英文](#)

在皇家学会科学文献目录中，有麦克斯韦署名的工作已经可以列出一长串了。现在，应该还要加上他对《大英百科全书》中原子、吸引作用、毛细作用等方面所作的很多贡献。另外，他还为编写出版《亨利·卡文迪什电学研究》付出了辛勤的劳动，整理了丰富而珍贵的手稿。这项工作是在最近的一两个月才问世的，书中记录着电学早期发展历程带给我们的很多意想不到的非凡启迪。我们希望不久之后能介绍一下这项工作。 [英文](#)

上面提到的工作已经显示了作者超常的科研能力，然而这些只是他已发表著作的冰山一角。如果我还补充说，麦克斯韦总是乐于帮助那些寻求建议或指引的人，而且他通读过很多好友的著作的校样（在上面所作的注释使其更加丰富，往往起到画龙点睛的作用），大家可能会觉得

十分惊讶，他哪来那么多时间完成这么多事情。

英文

很多读者一定还记得在我们的专栏中偶尔出现的那些非常尖锐的讽刺小诗，通常都是关于科学主题的，并且署名 $\frac{dp}{dt}$ ；在凯莱肖像画上的诗句中由行列式、-1的根、 n 维空间以及三次曲面上的27条线等很自然地组成的一首充满韵律的英文小诗；为鲍尔博士关于旋量的论文写的令人赞叹的简介；用出奇得体的伏特和欧姆组成的电报情书；特别是那篇《为女士所作的关于汤姆孙反射检流计的演讲》，所有这些都让人无法忘怀。当今世上没有人可以超越麦克斯韦在小诗中表现出的用几个清晰而简洁的句子就把问题的精髓概括出来的能力。这些小诗总是具有明确的目标，但是又把最尖锐的讽刺隐藏在迷人的纯真和纯朴的赞美之中。这里有两段没有发表的类似这种风格的片段：首先，是一个狂热的革命者的可怕想法——

我跟随着自己的感觉，
我要把电极放进我的脑子里；
要不我就吞下活生生的寄生虫，
我的生命会有崭新的感受——

另一个，是关于力的非客观性——

作用力和反作用力都消失了；
就在他们消失之前，
压力让他们静静地携起手来，合二为一，
然后，他们被放逐天涯。

英文

人们希望能够把这些散落的宝石集结出版，因为它们是现代最敏锐的智者中的一员闲暇时完成的作品，而又是如此有趣。每一首诗都证明了作者缜密的思维，并且很多都是以讽刺诗那种诙谐的手法写成的。

英文

我实在无法用语言表达麦克斯韦的早逝是多么巨大的损失，受到损失的不仅仅是他的朋友、剑桥大学和整个科学界，特别是，在充满空谈、伪科学和物质主义的今天，人们对常识、真科学以及宗教本身的探究也会因此受到巨大的损失。然而，脚踏实地的人决不会生活在空谈

中，至少从某种意义上讲，这样的人不会从世界上消失。麦克斯韦的精神会在他不朽的著作中与我们同在，并且这种精神会由那些受过他的教诲并以他为榜样的人，传承给下一代。 [英文](#)

（王静 翻译；鲍重光 审稿）

* 我们只能说布鲁斯特的观点所使用的主要论据是错误的，而三原色的主观性还没有完全被证实。

† 这个笔名是我建议他取的，因为我在著名的热力学第二定律 $\frac{dp}{dt} = J. C. M.$ 中发现了 he 名字的首字母缩写（而他本人也为这个定律能够建立在坚实的基础之上做了许多工作）。

On a New Kind of Rays*

W. C. Röntgen

This is an English translation of Wilhelm Conrad Röntgen's German report, in December 1895, of the discovery of X-rays. While experimenting with a cathode ray tube (also called a Crookes' or Lenard's tube, after earlier investigators), in which electrons or "kathode rays" are accelerated by electric fields, Röntgen found that the tube emits radiation that penetrates black paper and induces fluorescence in a screen on the other side. The rays also can penetrate matter and produce photographic images of "buried" objects such as bones. Röntgen deduces that these rays are not cathode rays, but seem instead to be akin to ultraviolet rays, yet with much greater penetrating power. He called them X-rays simply "for the sake of brevity". 中文

(1) A discharge from a large induction coil is passed through a Hittorf's vacuum tube, or through a well-exhausted Crookes' or Lenard's tube. The tube is surrounded by a fairly close-fitting shield of black paper; it is then possible to see, in a completely darkened room, that paper covered on one side with barium platinocyanide lights up with brilliant fluorescence when brought into the neighbourhood of the tube, whether the painted side or the other be turned towards the tube. The fluorescence is still visible at two metres distance. It is easy to show that the origin of the fluorescence lies within the vacuum tube. 中文

(2) It is seen, therefore, that some agent is capable of penetrating black cardboard which is quite opaque to ultra-violet light, sunlight, or arc-light. It is therefore of interest to investigate how far other bodies can be penetrated by the same agent. It is readily shown that all bodies possess this same transparency, but in very varying degrees. For example, paper is very transparent; the fluorescent screen will light up when placed behind a book of a thousand pages; printer's ink offers no marked resistance. Similarly the fluorescence shows behind two packs of cards; a single card does not visibly diminish the brilliancy of the light. So, again, a single thickness of tinfoil hardly casts a shadow on the screen; several have to be superposed to produce a marked effect. Thick blocks of wood are still transparent. Boards of pine two or three centimetres thick absorb only very little. A piece of sheet aluminium, 15 mm thick, still allowed the X-rays (as I will call the rays, for the sake of brevity) to pass, but greatly reduced the fluorescence. Glass plates of similar thickness behave similarly; lead glass is, however, much more opaque than glass free from lead. Ebonite several centimetres thick is transparent. If the hand be held before the fluorescent screen, the shadow shows the bones darkly, with only faint outlines of the surrounding tissues. 中文

Water and several other fluids are very transparent. Hydrogen is not markedly more permeable than air. Plates of copper, silver, lead, gold, and platinum also allow the rays to pass, but only when the metal is thin. Platinum 0.2 mm thick allows some rays to pass; silver and copper are more transparent. Lead 1.5 mm thick is practically opaque. If a square rod of wood 20 mm in the side be painted on one face with white lead, it casts little shadow when it is so turned that the painted face is parallel to the X-rays, but a strong shadow if the rays have to pass through the painted side. The salts of the metals, either solid or in solution, behave generally as the metals themselves. 中文

(3) The preceding experiments lead to the conclusion that the density

of the bodies is the property whose variation mainly affects their permeability. At least no other property seems so marked in this connection. But that the density alone does not determine the transparency is shown by an experiment wherein plates of similar thickness of Iceland spar, glass, aluminium, and quartz were employed as screens. Then the Iceland spar showed itself much less transparent than the other bodies, though of approximately the same density. I have not remarked any strong fluorescence of Iceland spar compared with glass (see below, No. 4). [中文](#)

(4) Increasing thickness increases the hindrance offered to the rays by all bodies. A picture has been impressed on a photographic plate of a number of superposed layers of tinfoil, like steps, presenting thus a regularly increasing thickness. This is to be submitted to photometric processes when a suitable instrument is available. [中文](#)

(5) Pieces of platinum, lead, zinc, and aluminium foil were so arranged as to produce the same weakening of the effect. The annexed table shows the relative thickness and density of the equivalent sheets of metal. [中文](#)

	Thickness	Relative thickness	Density
Platinum	0.018 mm	1	21.5
Lead	0.050 mm	3	11.3
Zinc	0.100 mm	6	7.1
Aluminium	3.500 mm	200	2.6

[中文](#)

From these values it is clear that in no case can we obtain the transparency of a body from the product of its density and thickness. The transparency increases much more rapidly than the product decreases. [中文](#)

(6) The fluorescence of barium platinocyanide is not the only noticeable action of the X-rays. It is to be observed that other bodies

exhibit fluorescence, *e.g.* calcium sulphide, uranium glass, Iceland spar, rock-salt, &c. [中文](#)

Of special interest in this connection is the fact that photographic dry plates are sensitive to the X-rays. It is thus possible to exhibit the phenomena so as to exclude the danger of error. I have thus confirmed many observations originally made by eye observation with the fluorescent screen. Here the power of the X-rays to pass through wood or cardboard becomes useful. The photographic plate can be exposed to the action without removal of the shutter of the dark slide or other protecting case, so that the experiment need not be conducted in darkness. Manifestly, unexposed plates must not be left in their box near the vacuum tube. [中文](#)

It seems now questionable whether the impression on the plate is a direct effect of the X-rays, or a secondary result induced by the fluorescence of the material of the plate. Films can receive the impression as well as ordinary dry plates. [中文](#)

I have not been able to show experimentally that the X-rays give rise to any calorific effects. These, however, may be assumed, for the phenomena of fluorescence show that the X-rays are capable of transformation. It is also certain that all the X-rays falling on a body do not leave it as such. [中文](#)

The retina of the eye is quite insensitive to these rays: the eye placed close to the apparatus sees nothing. It is clear from the experiments that this is not due to want of permeability on the part of the structures of the eye. [中文](#)

(7) After my experiments on the transparency of increasing thicknesses of different media, I proceeded to investigate whether the X-rays could be deflected by a prism. Investigations with water and carbon bisulphide in mica prisms of 30° showed no deviation either on the photographic or the fluorescent plate. For comparison, light rays

were allowed to fall on the prism as the apparatus was set up for the experiment. They were deviated 10 mm and 20 mm respectively in the case of the two prisms. [中文](#)

With prisms of ebonite and aluminium, I have obtained images on the photographic plate, which point to a possible deviation. It is, however, uncertain, and at most would point to a refractive index 1.05. No deviation can be observed by means of the fluorescent screen. Investigations with the heavier metals have not as yet led to any result, because of their small transparency and the consequent enfeebling of the transmitted rays. [中文](#)

On account of the importance of the question it is desirable to try in other ways whether the X-rays are susceptible of refraction. Finely powdered bodies allow in thick layers but little of the incident light to pass through, in consequence of refraction and reflection. In the case of the X-rays, however, such layers of powder are for equal masses of substance equally transparent with the coherent solid itself. Hence we cannot conclude any regular reflection or refraction of the X-rays. The research was conducted by the aid of finely-powdered rock-salt, fine electrolytic silver powder, and zinc dust already many times employed in chemical work. In all these cases the result, whether by the fluorescent screen or the photographic method, indicated no difference in transparency between the powder and the coherent solid.

[中文](#)

It is, hence, obvious that lenses cannot be looked upon as capable of concentrating the X-rays; in effect, both an ebonite and a glass lens of large size prove to be without action. The shadow photograph of a round rod is darker in the middle than at the edge; the image of a cylinder filled with a body more transparent than its walls exhibits the middle brighter than the edge. [中文](#)

(8) The preceding experiments, and others which I pass over, point to

the rays being incapable of regular reflection. It is, however, well to detail an observation which at first sight seemed to lead to an opposite conclusion. [中文](#)

I exposed a plate, protected by a black paper sheath, to the X-rays so that the glass side lay next to the vacuum tube. The sensitive film was partly covered with star-shaped pieces of platinum, lead, zinc, and aluminium. On the developed negative the star-shaped impression showed dark under platinum, lead, and, more markedly, under zinc; the aluminium gave no image. It seems, therefore, that these three metals can reflect the X-rays; as, however, another explanation is possible, I repeated the experiment with this only difference, that a film of thin aluminium foil was interposed between the sensitive film and the metal stars. Such an aluminium plate is opaque to ultra-violet rays, but transparent to X-rays. In the result the images appeared as before, this pointing still to the existence of reflection at metal surfaces. [中文](#)

If one considers this observation in connection with others, namely, on the transparency of powders, and on the state of the surface not being effective in altering the passage of the X-rays through a body, it leads to the probable conclusion that regular reflection does not exist, but that bodies behave to the X-rays as turbid media to light. [中文](#)

Since I have obtained no evidence of refraction at the surface of different media, it seems probable that the X-rays move with the same velocity in all bodies, and in a medium which penetrates everything, and in which the molecules of bodies are embedded. The molecules obstruct the X-rays, the more effectively as the density of the body concerned is greater. [中文](#)

(9) It seemed possible that the geometrical arrangement of the molecules might affect the action of a body upon the X-rays, so that, for example, Iceland spar might exhibit different phenomena

according to the relation of the surface of the plate to the axis of the crystal. Experiments with quartz and Iceland spar on this point lead to a negative result. [中文](#)

(10) It is known that Lenard, in his investigations on kathode rays, has shown that they belong to the ether, and can pass through all bodies. Concerning the X-rays the same may be said. [中文](#)

In his latest work, Lenard has investigated the absorption coefficients of various bodies for the kathode rays, including air at atmospheric pressure, which gives 4.10, 3.40, 3.10 for 1 cm, according to the degree of exhaustion of the gas in discharge tube. To judge from the nature of the discharge, I have worked at about the same pressure, but occasionally at greater or smaller pressures. I find, using a Weber's photometer, that the intensity of the fluorescent light varies nearly as the inverse square of the distance between screen and discharge tube. This result is obtained from three very consistent sets of observations at distances of 100 and 200 mm. Hence air absorbs the X-rays much less than the kathode rays. This result is in complete agreement with the previously described result, that the fluorescence of the screen can be still observed at 2 metres from the vacuum tube. In general, other bodies behave like air; they are more transparent for the X-rays than for the kathode rays. [中文](#)

(11) A further distinction, and a noteworthy one, results from the action of a magnet. I have not succeeded in observing any deviation of the X-rays even in very strong magnetic fields. [中文](#)

The deviation of kathode rays by the magnet is one of their peculiar characteristics; it has been observed by Hertz and Lenard, that several kinds of kathode rays exist, which differ by their power of exciting phosphorescence, their susceptibility of absorption, and their deviation by the magnet; but a notable deviation has been observed in all cases which have yet been investigated, and I think that such

deviation affords a characteristic not to be set aside lightly. 中文

(12) As the result of many researches, it appears that the place of most brilliant phosphorescence of the walls of the discharge-tube is the chief seat whence the X-rays originate and spread in all directions; that is, the X-rays proceed from the front where the kathode rays strike the glass. If one deviates the kathode rays within the tube by means of a magnet, it is seen that the X-rays proceed from a new point, *i.e.* again from the end of the kathode rays. 中文

Also for this reason the X-rays, which are not deflected by a magnet, cannot be regarded as kathode rays which have passed through the glass, for that passage cannot, according to Lenard, be the cause of the different deflection of the rays. Hence I conclude that the X-rays are not identical with the kathode rays, but are produced from the kathode rays at the glass surface of the tube. 中文

(13) The rays are generated not only in glass. I have obtained them in an apparatus closed by an aluminium plate 2 mm thick. I purpose later to investigate the behaviour of other substances. 中文

(14) The justification of the term “rays”, applied to the phenomena, lies partly in the regular shadow pictures produced by the interposition of a more or less permeable body between the source and a photographic plate or fluorescent screen. 中文



Fig. 1. Photograph of the bones in the fingers of a living human hand. The third finger has a ring upon it. 中文

I have observed and photographed many such shadow pictures. Thus, I have an outline of part of a door covered with lead paint; the image was produced by placing the discharge-tube on one side of the door, and the sensitive plate on the other. I have also a shadow of the bones of the hand (Fig. 1), of a wire wound upon a bobbin, of a set of weights in a box, of a compass card and needle completely enclosed in a metal case (Fig. 2), of a piece of metal where the X-rays show the want of homogeneity, and of other things. 中文

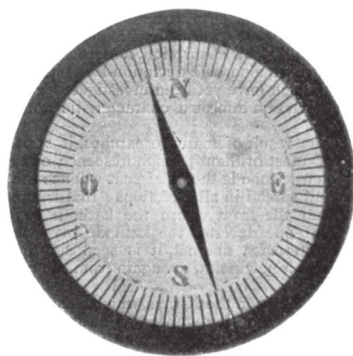


Fig. 2. Photograph of a compass card and needle completely enclosed in a metal case 中文

For the rectilinear propagation of the rays, I have a pin-hole photograph of the discharge apparatus covered with black paper. It is faint but unmistakable. 中文

(15) I have sought for interference effects of the X-rays, but possibly, in consequence of their small intensity, without result. 中文

(16) Researches to investigate whether electrostatic forces act on the X-rays are begun but not yet concluded. 中文

(17) If one asks, what then are these X-rays; since they are not kathode rays, one might suppose, from their power of exciting fluorescence and chemical action, them to be due to ultra-violet light. In opposition to this view a weighty set of considerations presents itself. If X-rays be indeed ultra-violet light, then that light must possess the following properties.

(a) It is not refracted in passing from air into water, carbon bisulphide, aluminium, rock-salt, glass or zinc.

(b) It is incapable of regular reflection at the surfaces of the above bodies.

(c) It cannot be polarised by any ordinary polarising media.

(d) The absorption by various bodies must depend chiefly on their density. 中文

That is to say, these ultra-violet rays must behave quite differently from the visible, infra-red, and hitherto known ultra-violet rays.

中文

These things appear so unlikely that I have sought for another hypothesis. 中文

A kind of relationship between the new rays and light rays appears to exist; at least the formation of shadows, fluorescence, and the production of chemical action point in this direction. Now it has been known for a long time, that besides the transverse vibrations which account for the phenomena of light, it is possible that longitudinal vibrations should exist in the ether, and, according to the view of some physicists, must exist. It is granted that their existence has not

yet been made clear, and their properties are not experimentally demonstrated. Should not the new rays be ascribed to longitudinal waves in the ether? [中文](#)

I must confess that I have in the course of this research made myself more and more familiar with this thought, and venture to put the opinion forward, while I am quite conscious that the hypothesis advanced still requires a more solid foundation. [中文](#)

(53, 274-276; 1896)

* By W. C. Röntgen. Translated by Arthur Stanton from the *Sitzungsberichte der Würzburger Physik-med. Gesellschaft*, 1895.

论一种新型的射线*

伦琴

此文译自威廉·康拉德·伦琴1895年12月的一份关于发现了X射线的德文报告。当伦琴用阴极射线管（早期的科研人员也把它称作克鲁克斯管或莱纳德管，管中的电子或“阴极射线”被电场加速）进行实验时，他发现阴极射线管发射的射线能够穿透黑色的纸并在其另一侧的屏幕上显示出荧光。这种射线还可以穿透物质，人们可以利用它拍摄出像骨骼这样的“被遮挡的”物质的照片。伦琴推测这种射线不属于阴极射线，它似乎更接近紫外线，但具有更强的穿透力。“为了简便起见”，他把这类射线称为“X射线”。 [英文](#)

（1）让大号感应线圈中产生的放电通过希托夫真空管，或者通过抽成真空的克鲁克斯管或莱纳德管。管子用黑纸包裹严实。在完全黑暗的房间里，将一面涂有铂氰酸钡的纸放在管子旁边，不论朝向管子的是涂有铂氰酸钡的一面还是没有涂的那面，纸都会被鲜艳的荧光照亮。在2米之外，这种荧光依然可见。很显然，荧光来源于真空管中。 [英文](#)

（2）由此可见，某些射线能够穿透这种紫外光、太阳光和电弧光都几乎不能透过的黑纸板。这就引起了人们研究这种射线到底能够多大程度地穿透其他物质的兴趣。很容易就能证明，所有物质对这种射线都是透明的，只是透明的程度大不相同。比如，纸是非常透明的，即使将荧光屏置于一本1,000页厚的书后面，我们仍然会在荧光屏上看到亮光，印刷油墨也不会造成明显的阻挡。类似地，单独一张卡片不会明显减弱光的强度，即使在两叠卡片后面我们也仍然能看到亮光。同样，单张锡箔纸的遮挡几乎不会使荧光屏上出现阴影，要产生明显的遮挡效果就必须重叠许多张锡箔纸。厚木块对于这种射线也是透明的。2~3厘米

厚的松木板的吸收效果非常微弱。15毫米厚的铝板也能使X射线（为了简便起见，我将称这种射线为X射线）透过，但是能够大幅度地减弱荧光。玻璃板的作用与厚度相近的铝板类似，不过，含铅的玻璃对这种射线的阻挡效果比不含铅的玻璃更强。几厘米厚的硬质橡胶也是透明的。如果把手放在荧光屏前，屏幕上就会显示出骨骼的黑影，而周围组织则只有模糊的轮廓。

[英文](#)

水和其他几种液体对于这种射线都是非常透明的。氢气的透明度并没有明显强于空气。铜、银、铅、金和铂质的金属板只有在很薄的时候才能使这种射线透过。0.2毫米的铂能使这种射线部分透过，银和铜则更透明一些。1.5毫米厚的铅板基本上是不透明的。将一根边长为20毫米的方木棒的一个侧面涂上铅白，当木棒涂有铅白的面与射线平行时，几乎不会产生阴影，但是当射线必须穿过涂有铅白的一面时，就会产生明显的阴影。不论是固态的金属盐还是金属盐溶液，一般都能像金属本身一样阻挡该射线。

[英文](#)

（3）根据上述实验我们可以得出结论：物质的密度是这样一种性质，它的变化主要影响射线在该物质中的透过程度。至少其他性质的影响看起来都不如密度明显。不过，单是密度还不能完全决定物质对该射线的透明度。我用厚度相近的冰洲石板、玻璃板、铝板和石英板作为样品进行的实验表明，尽管这些物质具有近似相同的密度，但冰洲石对该射线的透明度却比其他物质小得多。在用冰洲石进行的实验中，我从来没有观察到像用玻璃进行的实验中出现的那样明显的荧光（见下文，第4部分）。

[英文](#)

（4）对于所有物体，增加厚度都会提高其对X射线的阻挡程度。我们已经在照相底片上对阶梯状叠放的多层锡箔进行了成像，得到的图像表现出了厚度的这种有规律的增加。如果根据此原理制成适当的仪器，则可以作为光度计使用。

[英文](#)

（5）为了得到对X射线相同的减弱效果，我将铂、铅、锌和铝分别制成如下规格的金属片。附表给出了具有相同减弱效果的各种金属片的密度和相对厚度。

[英文](#)

	厚度	相对厚度	密度
铂	0.018 毫米	1	21.5
铅	0.050 毫米	3	11.3
锌	0.100 毫米	6	7.1
铝	3.500 毫米	200	2.6

英文

从这些数据中可以清楚地看出，我们不可能根据金属密度与其厚度的乘积来确定其透明度。透明度增加的速度比该乘积减少的速度快很多。

英文

(6) X射线所产生的显著作用并不是只能使铂氰酸钡发出荧光。可以观测到，X射线也能使其他一些物质发出荧光，例如硫化钙、铀玻璃、冰洲石和岩盐等。

英文

在这方面，特别让人感兴趣的是照相干版对X射线是敏感的。这就使我们可将实验现象记录下来以避免出现错误。利用照相的方法，我已经确认了很多最初通过肉眼在荧光屏上观测得到的实验结果。X射线穿透木块或纸板的能力很有用处。在对照相干版进行曝光时，可以不用除去遮光板或者其他保护盒，因此实验就不必在暗室中进行。当然，千万不要把装有未曝光照相干版的盒子放在真空管附近。

英文

干版上留下的影像到底是X射线的直接效应，还是由于干版材料发出的荧光引起的次级效应，现在看来还是一个令人疑惑的问题。和普通的干版一样，胶片也可以记录到影像。

英文

我还没能通过实验证明X射线是否可以产生热效应，不过我们猜测它可以，因为荧光现象表明X射线可以引起能量转移。而且可以肯定的是，照射在物体上的X射线并没有全部以荧光形式离开物体。

英文

人眼的视网膜对这种射线非常不敏感：即使眼睛离装置很近也看不见任何东西。实验结果清楚地表明，这并不是因为该射线在眼睛这部分结构中的透过程度不够。

英文

(7) 在通过实验研究了不同介质随着厚度增加对该射线的透明度的变化之后，我又研究了X射线是否会被棱镜偏转。在顶角为 30° 的云母

棱镜中分别装入水和二硫化碳进行实验，结果发现照相干版和荧光板上都没有显示出偏移。为了对照，我也用可见光在相同的实验装置上进行了实验，结果发现可见光在穿过上述两种棱镜时分别偏转了10毫米和20毫米。

英文

在使用硬质橡胶和铝制成的棱镜进行实验时，我得到的照相干版上的影像显示射线可能发生了偏转，不过这一点还不能确定，而且偏转所对应的折射率最多也只有1.05。使用荧光屏时则观测不到偏转。用较重金属进行的研究目前还没有任何结果，这是因为它们的透明度都很小，因而透射的射线非常微弱。

英文

考虑到X射线能否被偏转这个问题的重要性，我们就有必要尝试用其他方法来研究X射线能否发生折射。由于反射和折射的原因，微细粉末形成的厚层几乎不能使入射光透过。不过，这种多层粉末对于X射线的透明度与同质量同组成的整块固体是一样的。因此我们不能得出X射线具有常规的反射或折射特性的结论。我又对细粉末状的岩盐、电解得到的细银粉和已经在化学实验中使用了多次的锌粉进行了研究。所有研究结果都表明，不论是用荧光屏还是用照相的方法，粉末与相应的固体对X射线的透明度没有任何差别。

英文

因此，很明显透镜是不能会聚X射线的。事实上，大尺寸的玻璃透镜和硬质橡胶透镜对X射线都没有会聚作用，这已经得到了证明。圆柱的透视影像显示，中间部分的阴影比边缘更深一些；如果在圆柱内部填入透明度比柱体材料更高的物质，那么在得到的影像中，中间部分会比边缘更亮一些。

英文

(8) 上述实验和另外一些我未提及的实验，都表明这种射线不具备常规的反射能力。不过，我还是要详细介绍一个乍看上去似乎会使人们得出相反结论的实验。

英文

实验中，我将一块用黑纸套保护起来的玻璃干版置于X射线中，使其玻璃面靠近真空管，并用铂、铅、锌和铝质的星形金属片部分地遮挡干版的感光膜。在显影后的负片上，铂片和铅片下方出现了黑色的星形影像，锌片下方的影像更加清晰，而铝片并没有产生阴影。由此看来，前三种金属可以反射X射线。不过也可能有另外的解释。我又重复了这

一实验，这次唯一的不同之处是，我在感光膜和星形金属片之间插入了一块薄薄的铝箔。这块铝箔对紫外线是不透明的，但对X射线是透明的。结果出现了和以前一样的影像。这再次表明X射线在金属表面发生了反射。 [英文](#)

如果综合考虑这一观测结果和其他一些结果，包括关于粉末透明度的结果以及关于表面状态不能有效改变X射线穿过物体的路径的结果，我们就会得出这样一个可能的结论：对于X射线来说，并不存在普通意义上的反射，物体对于X射线的作用，就像混浊介质对于可见光一样。

[英文](#)

我还没有得到任何可以表明在不同介质表面X射线会发生折射的证据，这样看来，X射线在所有物质中的传播速度可能都相同，而且在一种渗透一切物质、包容各种物质分子的介质中也是一样的。随着物质密度的增大，其分子对X射线的阻挡效果也变得更加明显。 [英文](#)

(9) 分子的几何构型看起来可能会影响物质对X射线的阻挡作用，例如，对于冰洲石晶体而言，表面与晶轴之间相对取向的不同可能会导致不同的现象。但是，为此而用石英和冰洲石进行的实验却得到了阴性的结果。 [英文](#)

(10) 我们知道，莱纳德在对阴极射线的研究中已经指出，阴极射线属于以太，可以穿透任何物体。估计X射线可能也是这样的。 [英文](#)

莱纳德在最近的工作中研究了各种物体对阴极射线的吸收系数，比如一个大气压下的空气的吸收系数，根据放电管抽真空程度的不同，每一厘米对应的吸收系数分别是4.10、3.40和3.10。为了根据放电的本质来作出判断，我在基本相同的压强下进行了研究，不过偶尔也会用更高一点或更低一点的压强。利用韦伯光度计，我发现荧光的强度近似与屏幕到放电管距离的平方成反比。这个结论是根据三组非常一致的观测结果得到的，其观测距离分别为100毫米和200毫米。因此，空气对X射线的吸收比对阴极射线的吸收低很多。这一结果与前述的在距真空管2米处的屏幕上仍会出现荧光的结果是完全一致的。大体上，其他物质的性质与空气类似，它们对X射线比对阴极射线更加透明。 [英文](#)

(11) 另一个更明显也更值得关注的区别是磁场的作用。即使是在非常强的磁场中，我也没有观测到X射线的任何偏转。 [英文](#)

阴极射线在磁场作用下会发生偏转，这是它的独特性质之一。赫兹和莱纳德曾经观测到存在好几种阴极射线，它们的区别在于激发磷光的能力不同、被吸收的容易程度不同以及在磁场作用下的偏转不同。但是对于所有已经被研究过的阴极射线，人们都观测到了显著的偏转，我认为这种偏转代表了阴极射线的一种绝不该被忽视的特性。 [英文](#)

(12) 很多研究结果表明，放电管管壁上磷光最强的位置是在X射线产生并向四周各个方向发散的那个源头处，也就是说，X射线产生于阴极射线轰击玻璃的前沿位置。如果利用磁场使管中的阴极射线偏转，就会看到X射线从另一个位置上产生，但仍然是在阴极射线的终端位置。 [英文](#)

基于这一原因，我们不能把在磁场作用下并不偏转的X射线看作是已经穿透玻璃的阴极射线，因为按照莱纳德的看法，这条通道不可能由阴极射线的不同偏转造成的。由此我断定，X射线与阴极射线是不同的，它是阴极射线作用于真空管的玻璃表面而产生的。 [英文](#)

(13) 并不是只有用玻璃才能产生X射线。我曾利用一种被2毫米厚的铝板包裹起来的装置得到了X射线。以后我将研究其他物质是否也能产生X射线。 [英文](#)

(14) 在描述这种现象时我使用了“射线”这个词，这在一定程度上是因为，将不太透明的物体插入到源和照相干版或荧光屏之间时会产生规则的阴影。 [英文](#)

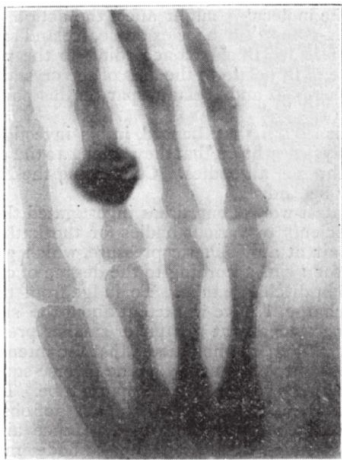


图1．活人手指（第三指上戴着一枚戒指）骨骼的影像 [英文](#)

我已经观察并用照相记录了很多这样的阴影。由此，我记录下了门的局部轮廓。我是用含铅涂料刷了门的轮廓，然后把放电管放置在门的一侧，而把光敏照相干版放置在另一侧，这样就得到了门的局部轮廓的影像。我还记录了其他许多物体的阴影，这包括手掌骨骼（图1）、缠在绕线筒上的导线、一套装在盒子里的砝码、完全密封于金属盒子中的罗经刻度盘和指针（图2）、一块在X射线下显示出不均匀缺陷的金属片，以及其他一些物品。 [英文](#)

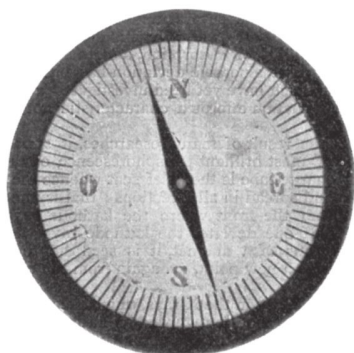


图2．完全密封于金属盒子中的罗经刻度盘和指针的影像 [英文](#)

为了说明射线的直线传播，我用针孔照相的方法拍摄了用黑纸覆盖的放电装置。照片虽然有些模糊，但却可以明白无误地分辨出装置。

[英文](#)

（15）我曾经试图寻找X射线的干涉效应，但并没有检测到，这可能是由于强度太低的缘故。 [英文](#)

(16) 关于静电力对X射线是否有作用的研究工作正在进行，但目前尚无结论。 英文

(17) 也许有人会问X射线到底是什么。既然这种射线不是阴极射线，有人可能就会根据其激发荧光和引发化学反应的能力猜想它是紫外光。然而，一系列认真的思考都是反对这种观点的。如果X射线真是一种紫外光，那么这种紫外光就必须具有如下性质：

(a) 它在由空气进入水、二硫化碳、铝、岩盐、玻璃或锌时，不会发生折射。

(b) 它在上述物质的表面不会发生常规的反射。

(c) 任何普通的偏振介质都不能使它偏振。

(d) 不同物质对它的吸收主要取决于该物质的密度。 英文

也就是说，这种紫外线必须具有与可见光、红外线以及迄今为止已知的紫外线都十分不同的性质。 英文

看起来这些是很难成立的，因此我想到了另一种假说。 英文

这种新型的射线与普通光之间看起来应该存在着某种关联，至少在形成阴影、激发荧光以及引发化学反应这些方面都是相似的。长期以来我们都知道，除了能够解释光现象的横向振动外，在以太中可能存在纵向振动，某些物理学家甚至认为纵向振动是必定存在的。尽管目前人们还不完全清楚纵向振动是否存在，也没有通过实验论证这种纵向振动的性质，但是，难道我们就不能认为这种新型的射线属于以太中的纵波吗？ 英文

我必须要承认的是，在研究过程中我越来越倾向于这一观点。另外我也十分清楚这一新假说还需要更为可靠的证据，我承认在目前的情况下抛出这一观点是比较冒昧的。 英文

(王耀杨 翻译；江丕栋 审稿)

* 作者为伦琴。由阿瑟·斯坦顿译自1895年的《维尔茨堡物理学医学学会会刊》。

Professor Röntgen's Discovery

A. A. C. Swinton

One of the most sobering things about this verification of Röntgen's discovery of X-rays, less than a month after they were first reported, is that it shows how tepid the reception of great discoveries can be among scientific peers. Campbell-Swinton hints that the newspapers have been getting excited over a phenomenon that is not "entirely novel". But that is because he somewhat misinterprets Röntgen's results. Swinton insists on regarding the X-rays as "some portion of the kathode radiations", and points out that cathode rays are already known to produce photographic images—missing Röntgen's claim that his X-rays are not cathode rays at all.

中文

THE newspaper reports of Prof. Röntgen's experiments have, during the past few days, excited considerable interest. The discovery does not appear, however, to be entirely novel, as it was noted by Hertz that metallic films are transparent to the kathode rays from a Crookes or Hittorf tube, and in Lenard's researches, published about two years ago, it is distinctly pointed out that such rays will produce photographic impressions. Indeed, Lenard, employing a tube with an aluminium window, through which the kathode rays passed out with comparative ease, obtained photographic shadow images almost identical with those of Röntgen, through pieces of cardboard and aluminium interposed between the window and the photographic

plate. 中文

Prof. Röntgen has, however, shown that this aluminium window is unnecessary, as some portion of the kathode radiations that are photographically active will pass through the glass walls of the tube. Further, he has extended the results obtained by Lenard in a manner that has impressed the popular imagination, while, perhaps most important of all, he has discovered the exceedingly curious fact that bone is so much less transparent to these radiations than flesh and muscle, that if a living human hand be interposed between a Crookes tube and a photographic plate, a shadow photograph can be obtained which shows all the outlines and joints of the bones most distinctly.

中文

Working upon the lines indicated in the telegrams from Vienna, recently published in the daily papers, I have, with the assistance of Mr. J. C. M. Stanton, repeated many of Prof. Röntgen's experiments with entire success. According to one of our first experiments, an ordinary gelatinous bromide dry photographic plate was placed in an ordinary camera back. The wooden shutter of the back was kept closed, and upon it were placed miscellaneous articles such as coins, pieces of wood, carbon, ebonite, vulcanised fibre, aluminium, &c., all being quite opaque to ordinary light. Above was supported a Crookes tube, which was excited for some minutes. On development, shadows of all the articles placed on the slide were clearly visible, some being more opaque than others. Further experiments were tried with thin plates of aluminium or of black vulcanised fibre interposed between the objects to be photographed and the sensitive surface, this thin plate being used in place of the wood of the camera back. In this manner sharper shadow pictures were obtained. While most thick metal sheets appear to be entirely opaque to the radiations, aluminium appears to be relatively transparent. Ebonite, vulcanised fibre, carbon, wood, cardboard, leather and slate are all very

transparent, while, on the other hand, glass is exceedingly opaque. Thin metal foils are moderately opaque, but not altogether so. 中

文

As tending to the view that the radiations are more akin to ultraviolet than to infra-red light, it may be mentioned that a solution of alum in water is distinctly more transparent to them than a solution of iodine in bisulphide of carbon. 中文

So far as our own experiments go, it appears that, at any rate without very long exposures, a sufficiently active excitation of the Crookes tube is not obtained by direct connection to an ordinary Rhumkorff induction coil, even of a large size. So-called high frequency currents, however, appear to give good results, and our own experiments have been made with the tube excited by current obtained from the secondary circuit of a Tesla oil coil, through the primary of which were continuously discharged twelve half-gallon Leyden jars, charged by an alternating current of about 20,000 volts pressure, produced by a transformer with a spark-gap across its high-pressure terminals.

中文

For obtaining shadow photographs of inanimate objects, and for testing the relative transparency of different substances, the particular form of Crookes tube employed does not appear to greatly signify, though some forms are, we find, better than others. When, however, the human hand is to be photographed, and it is important to obtain sharp shadows of the bones, the particular form of tube used and its position relative to the hand and sensitive plate appear to be of great importance. So far, owing to the frequent destruction of the tubes, due to overheating of the terminals, we have not been able to ascertain exactly the best form and arrangement for this purpose, except that it appears desirable that the electrodes in the tube should consist of flat and not curved plates, and that these plates should be of small dimensions. 中文

The accompanying photograph of a living human hand (Fig. 1) was exposed for twenty minutes through an aluminium sheet 0.0075 in thickness, the Crookes tube, which was one of the kind containing some white phosphorescent material (probably sulphide of barium), being held vertically upside down, with its lowest point about two inches above the centre of the hand. 中文

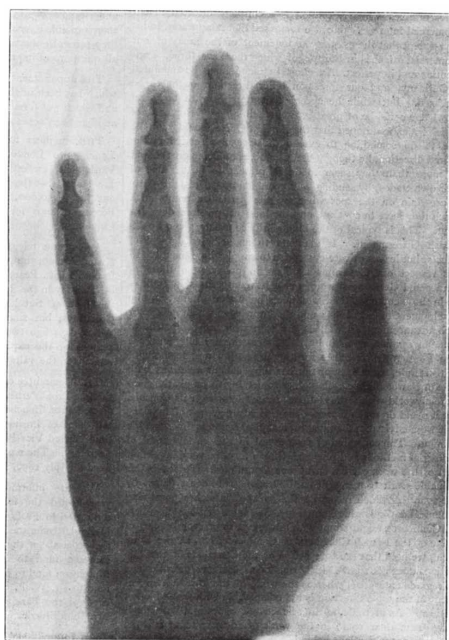


Fig. 1. Photograph of a living human hand 中文

By substituting a thin sheet of black vulcanised fibre for the aluminium plate, we have since been able to reduce the exposure required to four minutes. Indeed with the aluminium plate, the twenty minutes' exposure appears to have been longer than was necessary. Further, having regard to the great opacity of glass, it seems probable that where ordinary Crookes tubes are employed, a large proportion of the active radiations must be absorbed by the glass of the tube itself. If this is so, by the employment of a tube partly constructed of aluminium, as used by Lenard, the necessary length of exposure could be much reduced. 中文

伦琴教授的发现

斯温顿

距离伦琴最初宣布发现X射线还不到一个月，就有了这篇对伦琴的发现查证，这是一个应该引起人们警醒的事例，它表明科学界同行对重大发现的态度也会是冷淡的。坎贝尔-斯温顿含蓄地指出，报业为之感到兴奋的现象实际上并不是一个“全新的”现象。但他之所以这样说是因为他在某种程度上误会了伦琴得到的结论。斯温顿坚持把X射线看作是“阴极射线的一部分”，并指出人们早就知道阴极射线能够用于拍摄照片，可他没有注意到伦琴所称的X射线根本就不是阴极射线。 [英文](#)

前一段时间，关于伦琴教授的实验的新闻报道引起了相当广泛的关注。不过，这一发现似乎并不是全新的，因为赫兹就曾注意到从克鲁克斯管或希托夫管中发射出来的阴极射线能够穿透金属薄片，而大约两年前莱纳德就在其发表的研究报告中明确地指出这种射线可以产生影像。莱纳德使用了一个带铝窗的管子，阴极射线可以比较容易地从此窗中穿出，伦琴的实验中则是射线穿过了插在管窗与照相干版之间的纸板和铝片。实际上，莱纳德得到了与伦琴的结果几乎完全一样的阴影图像。

[英文](#)

不过，伦琴教授已经阐明这个铝窗并不是必需的，因为一部分能够引起成像的阴极辐射是从玻璃管壁中穿出的。此外，他还以一种能给人们留下深刻印象的方式推广了莱纳德得到的结果，而也许最为重要的是，他发现了一个极为新奇的现象，即这种辐射穿透骨骼的能力比穿透肌肉的能力差很多，如果将活人的手置于克鲁克斯管与照相干版之间，就能得到一张非常清晰地显示出骨骼关节轮廓的阴影图像。 [英文](#)

最近，许多日报都刊载了来自维也纳的电报，根据其中提供的线

索，在斯坦顿先生的协助下，我已经完全成功地重复了伦琴教授的很多实验。在最初的一次实验中，我们将一张普通的凝胶溴化物照相干版放置在普通相机后面。背面的木质快门始终保持关闭状态，并紧接着放置各种物品，诸如硬币、木块、炭、硬质橡胶、硬化纤维和铝等，所有这些物品对于普通的可见光都是完全不透明的。在这些物品上方固定一个已经激发了几分钟的克鲁克斯管。显影后，放置的所有物品的阴影都清晰可见，其中一些物品的阴影比其他的更加明显。在后来的实验中，我们尝试着将薄铝板或黑色硬化纤维薄板插入待成像的物体与感光表面之间，这一薄板用来代替相机后的木质快门。用这种方式我们得到了更加清晰的阴影图像。大部分厚金属板对于这种辐射似乎都是完全不透明的，而铝板则似乎比较透明。硬质橡胶、硬化纤维、炭、木块、纸板、皮革以及石板都是非常透明的，相反，玻璃则是非常不透明的。薄金属板是中等透明的，不过也不全是这样。 [英文](#)

为了支持该辐射更类似于紫外线而不是红外线的观点，我们要说明一下，与碘的二硫化碳溶液相比，明矾的水溶液对该辐射的透明度明显好得多。 [英文](#)

就我们的实验情况来说，如果不进行很长时间的曝光，单靠将一个普通的拉姆科夫感应线圈与克鲁克斯管直接相连，即使是用大号的线圈，看起来似乎也无法使克鲁克斯管产生足够引起成像活性的激发辐射。不过，我们常说的高频电流看来能够给出好的结果。我们在实验中使用的克鲁克斯管，是由特斯拉油线圈的次级电路产生的电流来激发的，通过其初级电路的是连续放电的12个半加仑莱顿瓶，这些莱顿瓶通过电压约为20,000伏特的交流电进行充电，此交流电由一高压端带有放电间隙的变压器产生。 [英文](#)

要获得无生命物体的阴影或检验不同物质对此种辐射的相对透明度，使用哪种结构的克鲁克斯管看起来并不是非常要紧，尽管我们发现某些结构的管子比另外一些好一点。但是，在获取人手的影像时，重要的是得到骨骼的清晰阴影，那么所使用的管子的特殊结构以及管子相对于人手和感光干版的位置就显得至关重要了。到目前为止，由于管子经常因其末端过热而毁坏，我们还没能弄清楚对于上述目的来说什么样的管子结构和摆放位置是最好的，不过能够确定的是，管子中的电极应该

采用平板电极而不是曲面电极，并且应该用尺寸较小的电极板。 英文

文

本文所附的活人手掌的影像（图1）是该辐射穿过厚度为0.0075的铝片持续曝光20分钟而得到的，实验中使用的克鲁克斯管中包含某种白色磷光物质（可能是硫化钡），管子颠倒后垂直放置，其最低点位于掌心上方大约2英寸处。 英文

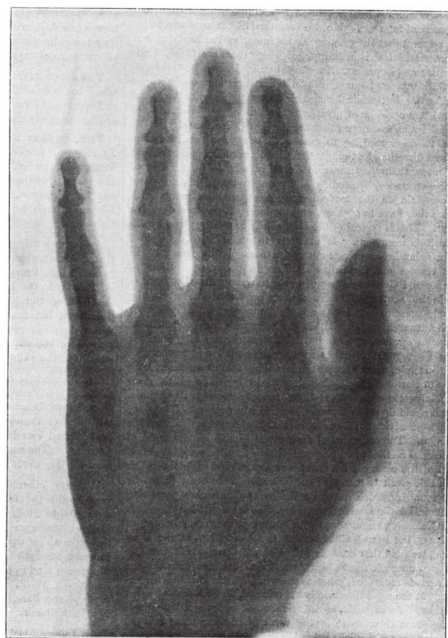


图1．活人手掌的影像 英文

用一块黑色硬化纤维薄板代替铝板后，我们发现可以把曝光时间缩短到4分钟。实际上，在使用铝板的情况下，20分钟的曝光时间似乎也比必需的曝光时间长一些。此外，考虑到玻璃很显著的不透明性，看来在使用普通克鲁克斯管时，大部分能够形成影像的辐射一定被管子自身的玻璃壁吸收了。如果确实如此，那么使用部分为铝质材料的管子（如同莱纳德所用的那样）的话，必需的曝光时间应该会大大缩短。 英文

文

（王耀杨 翻译；江丕栋 审稿）

New Experiments on the Kathode Rays*

M. J. Perrin

Physicists were puzzled by cathode rays, which carried energy from a negative electrode (cathode) toward a positive electrode inside a vacuum tube. Experimenters had determined that they originated at the cathode, but could not say what they were. In this classic paper the French physicist Jean Perrin reports experiments that helped to clarify the mystery. He placed into a cathode ray tube a metal cylinder linked to an electroscope, which would measure any charge deposited into it. When the cathode rays were directed into the tube, Perrin detected a significant negative charge. Perrin speculated that the charge carriers were negative ions created near the cathode. In fact they were electrons, as J. J. Thomson discovered one year later. [中文](#)

(1) Two hypotheses have been propounded to explain the properties of the kathode rays. [中文](#)

Some physicists think with Goldstein, Hertz, and Lenard, that this phenomenon is like light, due to vibrations of the ether†, or even that it is light of short wavelength. It is easily understood that such rays may have a rectilinear path, excite phosphorescence, and affect photographic plates. [中文](#)

Others think, with Crookes and J. J. Thomson, that these rays are

formed by matter which is negatively charged and moving with great velocity, and on this hypothesis their mechanical properties, as well as the manner in which they become curved in a magnetic field, are readily explicable. [中文](#)

This latter hypothesis has suggested to me some experiments which I will now briefly describe, without for the moment pausing to inquire whether the hypothesis suffices to explain all the facts at present known, and whether it is the only hypothesis that can do so. Its adherents suppose that the kathode rays are negatively charged; so far as I know, this electrification has not been established, and I first attempted to determine whether it exists or not. [中文](#)

(2) For that purpose I had recourse to the laws of induction, by means of which it is possible to detect the introduction of electric charges into the interior of a closed electric conductor, and to measure them. I therefore caused the kathode rays to pass into a Faraday's cylinder. For this purpose I employed the vacuum tube represented in Fig. 1. A B C D is a tube with an opening α in the centre of the face B C. It is this tube which plays the part of a Faraday's cylinder. A metal thread soldered at S to the wall of the tube connects this cylinder with an electroscope. [中文](#)

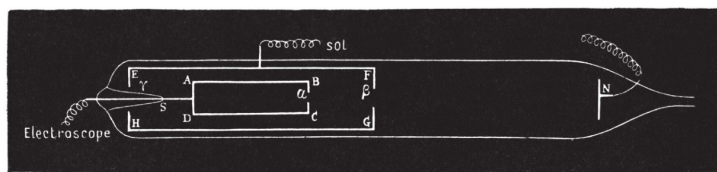


Fig. 1 [中文](#)

E F G H is a second cylinder in permanent communication with the earth, and pierced by two small openings at β and γ ; it protects the Faraday's cylinder from all external influence. Finally, at a distance of about 0.10 m in front of F G, was placed an electrode N. The electrode N served as kathode; the anode was formed by the protecting cylinder E F G H; thus a pencil of kathode rays passed into the Faraday's

cylinder. This cylinder invariably became charged with negative electricity. 中文

The vacuum tube could be placed between the poles of an electromagnet. When this was excited, the cathode rays, becoming deflected, no longer passed into the Faraday's cylinder, and this cylinder was then not charged; it, however, became charged immediately the electromagnet ceased to be excited. 中文

In short, the Faraday's cylinder became negatively charged when the cathode rays entered it, and only when they entered it; *the cathode rays are then charged with negative electricity.* 中文

The quantity of electricity which these rays carry can be measured. I have not finished this investigation, but I shall give an idea of the order of magnitude of the charges obtained when I say that for one of my tubes, at a pressure of 20 microns of mercury, and for a single interruption of the primary of the coil, the Faraday's cylinder received a charge of electricity sufficient to raise a capacity of 600 C. G. S. units to 300 volts. 中文

(3) The cathode rays being negatively charged, the principle of the conservation of electricity drives us to seek somewhere the corresponding positive charges. I believe that I have found them in the very region where the cathode rays are formed, and that I have established the fact that they travel in the opposite direction, and fall upon the cathode. In order to verify this hypothesis, it is sufficient to use a hollow cathode pierced with a small opening by which a portion of the attracted positive electricity might enter. This electricity could then act upon a Faraday's cylinder inside the cathode. 中文

The protecting cylinder E F G H with its opening β fulfilled these conditions, and this time I therefore employed it as the cathode, the electrode N being the anode. The Faraday's cylinder is then invariably charged with *positive electricity*. The positive charges were of the order

of magnitude of the negative charges previously obtained. 中文

Thus, at the same time as negative electricity is *radiated* from the kathode, positive electricity travels towards that kathode. 中文

I endeavoured to determine whether this positive flux formed a second system of rays absolutely symmetrical to the first. 中文

(4) For that purpose I constructed a tube (Fig. 2) similar to the preceding, except that between the Faraday's cylinder and the opening β was placed a metal diaphragm pierced with an opening β' , so that the positive electricity which entered by β could only affect the Faraday's cylinder if it also traversed the diaphragm β' . Then I repeated the preceding experiments. 中文

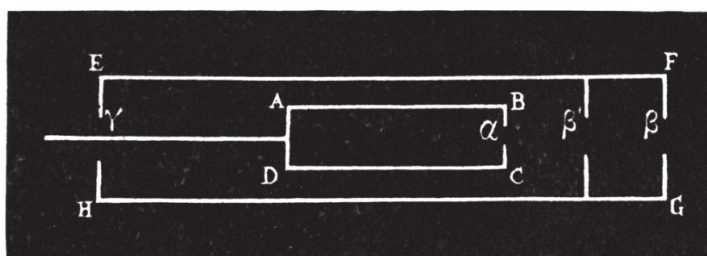


Fig. 2 中文

When N was the kathode, the rays emitted from the kathode passed through the two openings β and β' without difficulty, and caused a strong divergence of the leaves of the electroscope. But when the protecting cylinder was the kathode, the positive flux, which, according to the preceding experiment, entered at β , did not succeed in separating the gold leaves except at very low pressures. When an electrometer was substituted for the electroscope, it was found that the action of the positive flux was real but very feeble, and increased as the pressure decreased. In a series of experiments at a pressure of 20 microns, it raised a capacity of 2,000 C. G. S. units to 10 volts; and at a pressure of 3 microns, during the same time, it raised the potential to 60 volts.‡ 中文

By means of a magnet this action could be entirely suppressed. 中文

(5) These results as a whole do not appear capable of being easily reconciled with the theory which regards the kathode rays as an ultra-violet light. On the other hand, they agree well with the theory which regards them as a material radiation, and which, as it appears to me, might be thus enunciated. 中文

In the neighbourhood of the kathode, the electric field is sufficiently intense to break into pieces (*into ions*) certain of the molecules of the residual gas. The negative ions move towards the region where the potential is increasing, acquire a considerable speed, and form the kathode rays; their electric charge, and consequently their mass (at the rate of one valence-gramme for 100,000 Coulombs) is easily measurable. The positive ions move in the opposite direction; they form a diffused brush, sensitive to the magnet, and not a radiation in the correct sense of the word.§ 中文

(53, 298-299; 1896)

* Translation of a paper by M. Jean Perrin, read before the Paris Academy of Sciences on December 30, 1895.

† These vibrations might be something different from light; recently M. Jaumann, whose hypotheses have since been criticised by M. H. Poincaré, supposed them to be longitudinal.

‡ The breaking of the tube has temporarily prevented me from studying the phenomenon at lower pressures.

§ This work has been carried out in the laboratory of the Normal School, and in that of M. Pellat at the Sorbonne.

关于阴极射线的新实验*

佩兰

物理学家们对在真空管中把能量从负极（阴极）带到正极的阴极射线感到迷惑不解。实验可以证明它们来自阴极，但不能说明它们到底是什么。法国物理学家让·佩兰在这篇经典论文中用实验揭开了阴极射线的神秘面纱。他在阴极射线管内放置了一个与验电器相连的金属圆柱体，验电器可以测量进入其中的电荷。当阴极射线进入真空管时，佩兰检测到了大量的负电荷。佩兰推测这些载流子是在阴极附近产生的负离子。实际上它们就是一年之后汤姆逊发现的电子。

[英文](#)

（1）现在可以解释阴极射线性质的假说有两种。

[英文](#)

一部分物理学家和戈尔德施泰因、赫兹、莱纳德的意見一致，认为这种现象和光一样，是由以太的振动引起的[†]，或者它就是一种短波长的光。很容易就可以理解，这种射线可能是沿直线传播的，能激发磷光，而且可以使照相干版感光。

[英文](#)

另一部分人则与克鲁克斯、汤姆逊持相同的观点，认为这种射线是由带负电的物质组成，并以极快的速度运动。用这种假说可以解释它们的力学性质，也可以很容易地说明为什么它们在磁场中的路径会弯曲。

[英文](#)

后一种假说启发我进行了一些实验，我将在这里简单地描述这些实验，暂时先不管这个假说是否能解释目前所有已知的现象，或者是否只有这一种假说可以解释这些现象。它的支持者认为阴极射线是带负电的，而据我所知，这种带电性还没有被确认，我首先要确定它是否带电。

[英文](#)

(2) 为了达到这个目的, 我将借助电磁感应定律, 用这个定律, 我们可以检测引入闭合导体内部的电量, 并且进行定量测量。因此, 我让阴极射线通过法拉第圆筒。为此我设计了如图1所示的真空管。A B C D是一根管子, 在B C面中心的 α 处有一个小孔。正是这根管子起到了法拉第圆筒的作用。一根焊接在管壁S处的金属线将圆筒和外部的验电器连接起来。

英文

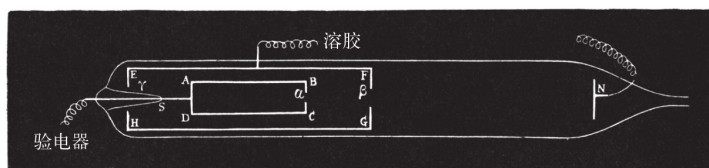


图1 英文

E F G H是另一个圆筒, 永久接地, 并且在 β 、 γ 处穿有两个小孔; 这个圆筒可以屏蔽外界对法拉第圆筒的干扰。最后, 在F G前面大约0.1米的地方有一个电极N。电极N作为阴极, 屏蔽圆筒E F G H作为阳极。在这样的条件下, 将一束阴极射线通入法拉第圆筒, 这个圆筒将一直带负电。

英文

真空管可以放置在电磁铁的两极之间。当电磁铁通电时, 阴极射线将发生偏转, 不能再通入法拉第圆筒, 这个圆筒也将不再带电, 而当电磁铁断电之后, 法拉第圆筒马上又带电了。

英文

简单地说就是, 当且仅当有阴极射线进入时, 法拉第圆筒带负电, 所以阴极射线一定带负电。

英文

射线所带的电量可以被测量出来。我还没有完成这项研究, 但是我可以给出一个有关所获电量的数量级的概念, 对于一个压力为20微米汞柱的真空管, 将初级线圈截断, 法拉第圆筒接收的电量足以使600单位(厘米克秒制)的电容器的电势差提高到300伏特。

英文

(3) 阴极射线带负电, 根据电荷守恒定律, 我们应该能在某处找到相应的正电荷。我确信我已经在阴极射线产生的地方找到了正电荷, 我认为它们向相反的方向运动, 而后撞在了阴极上。为了证明这种说法, 只要用一个中空的阴极就行, 在阴极上穿一个小孔, 以使一部分被吸引过来的正电荷可以由此通过。进入阴极的正电荷会影响阴极内部的

法拉第圆筒。 英文

带有小孔 β 的屏蔽圆筒E F G H满足以上条件，因此这一回我用E F G H作阴极，电极N作阳极。这样，法拉第圆筒就会一直带正电。其所带正电荷和前面所测的负电荷的数量级相同。 英文

这说明，在阴极发射负电荷的同时，正电荷也在向阴极运动。
英文

我下决心要确定这种正电流是否能形成另一个和阴极射线完全对称的射线系统。 英文

(4) 为此我构造了一个和前面类似的管子（见图2），与前面管子唯一的不同之处是，在法拉第圆筒和小孔 β 之间放置了一个金属膜片，膜片上有一个小孔 β' ，这样，从 β 进入的正电荷只有在也通过 β' 的情况下才能作用于法拉第圆筒。我用这个装置重复了上面的实验。 英文

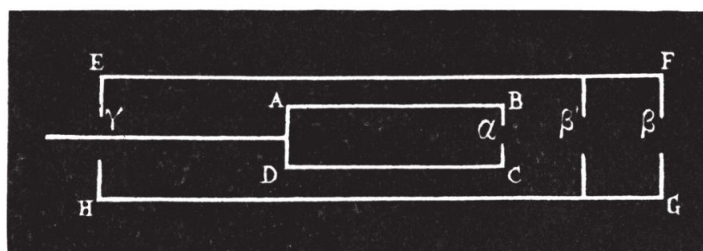


图2 英文

当N作为阴极时，由阴极发射的射线可以顺利地通过 β 和 β' 两个孔，使验电器的两个叶片张得很大。但是当屏蔽圆筒作为阴极时，根据前述的实验，通过 β 进入的正电流并没有使验电器的金箔张开，除非是在压力很低的情况下。当用静电计代替验电器时，可以看到正电流的确存在但非常微弱，并随着压力的减小而增大。在20微米汞柱条件下进行的一系列实验中，这一正电流可以把2,000单位（厘米克秒制）的电容器电势差提高到10伏特；在压力为3微米汞柱时，同样时间内电势差被提高到了60伏特。‡ 英文

利用磁铁可以完全地抑制这种作用。 英文

(5) 总的来说，把阴极射线看作是紫外线的假说似乎不太容易解

释这些实验结果。另一方面，这些实验结果与认为阴极射线是一种物质辐射的假说符合得很好，在我看来，这些实验结果恐怕只能这么解释。

英文

在阴极附近，电场强度强到足以把一定量的残余气体分子打成碎片（变成离子）。负离子向着电势增加的方向运动，速度很大，这形成了阴极射线，它们的电量很容易被测定，从而其质量（100,000库仑对应1克当量）也很容易得到。正离子向相反方向运动，形成一个发散的尾巴，对磁场非常敏感，准确地说这就不是辐射了。§ 英文

（王锋 翻译；江丕栋 审稿）

* 这篇文章翻译自让·佩兰在1895年12月30日向巴黎科学院宣读的论文。

† 这种振动可能与光有些不同。最近，尧曼（其猜想曾经被普安卡雷批判过）提出这种振动可能是纵向的。

‡ 真空管的爆裂使我暂时无法再在低压条件下研究这一现象。

§ 这项研究是在师范学院的实验室和索邦大学佩拉的实验室中进行的。

The Effect of Magnetisation on the Nature of Light Emitted by a Substance*

P. Zeeman

Does a magnetic field influence the light emitted by an atom? Here Pieter Zeeman reports the first evidence that it does. Zeeman heated sulphur in a ceramic chamber with transparent ends, and placed the chamber in a magnetic field. With the light of an arc lamp, he then measured the absorption spectrum and found a broadening of certain lines, attributing this to a change in the frequency of the absorbed light. Zeeman noted that the polarization of light emitted in the presence of a field behaves as predicted by Lorentz, owing to the circular motion of charged particles within the atom. He estimates the charge/mass ratio for these particles as being about 10^7 . [中文](#)

IN consequence of my measurements of Kerr's magneto-optical phenomena, the thought occurred to me whether the period of the light emitted by a flame might be altered when the flame was acted upon by magnetic force. It has turned out that such an action really occurs. I introduced into an oxyhydrogen flame, placed between the poles of a Ruhmkorff's electromagnet, a filament of asbestos soaked in common salt. The light of the flame was examined with a Rowland's grating. Whenever the circuit was closed both D lines were seen to

widen. [中文](#)

Since one might attribute the widening to the known effects of the magnetic field upon the flame, which would cause an alteration in the density and temperature of the sodium vapour, I had resort to a method of experimentation which is much more free from objection.

[中文](#)

Sodium was strongly heated in a tube of biscuit porcelain, such as Pringsheim used in his interesting investigations upon the radiations of gases. The tube was closed at both ends by plane parallel glass plates, whose effective area was 1 cm. The tube was placed horizontally between the poles, at right angles to the lines of force. The light of an arc lamp was sent through. The absorption spectrum showed both D lines. The tube was continuously rotated round its axis to avoid temperature variations. Excitation of the magnet caused immediate widening of the lines. It thus appears very probable that the period of sodium light is altered in the magnetic field. It is remarkable that Faraday, as early as 1862, had made the first recorded experiment in this direction, with the incomplete resources of that period, but with a negative result (Maxwell, "Collected Works", vol. II, p. 790). [中文](#)

It has been already stated what, in general, was the origin of my own research on the magnetisation of the lines in the spectrum. The possibility of an alteration of period was first suggested to me by the consideration of the accelerating and retarding forces between the atoms and Maxwell's molecular vortices; later came an example suggested by Lord Kelvin, of the combination of a quickly rotating system and a double pendulum. However, a true explanation appears to me to be afforded by the theory of electric phenomena propounded by Prof. Lorentz. [中文](#)

In this theory, it is considered that, in all bodies, there occur small

molecular elements charged with electricity, and that all electrical processes are to be referred to the equilibrium or motion of these “ions”. It seems to me that in the magnetic field the forces directly acting on the ions suffice for the explanation of the phenomena.

中文

Prof. Lorentz, to whom I communicated my idea, was good enough to show me how the motion of the ions might be calculated, and further suggested that if my application of the theory be correct there would follow these further consequences: that the light from the edges of the widened lines should be circularly polarised when the direction of vision lay along the lines of force; further, that the magnitude of the effect would lead to the determination of the ratio of the electric charge the ion bears to its mass. We may designate the ratio e/m . I have since found by means of a quarter-wave length plate and an analyser, that the edges of the magnetically-widened lines are really circularly polarised when the line of sight coincides in direction with the lines of force. An altogether rough measurement gives 10^7 as the order of magnitude of the ratio e/m when e is expressed in electromagnetic units.

中文

On the contrary, if one looks at the flame in a direction at right angles to the lines of force, then the edges of the broadened sodium lines appear plane polarised, in accordance with theory. Thus there is here direct evidence of the existence of ions.

中文

This investigation was conducted in the Physical Institute of Leyden University, and will shortly appear in the “Communications of the Leyden University”.

中文

I return my best thanks to Prof. K. Onnes for the interest he has shown in my work.

中文

P. Zeeman: Amsterdam.

* Translated by Arthur Stanton from the *Proceedings of the Physical Society of Berlin*.

磁化对物质发射的光的性质的影响*

塞曼

磁场会影响原子发射的光吗？彼得·塞曼在这篇报告中首次证明这种效应是存在的。塞曼在两端透明的陶瓷真空室中加热硫磺，并把这个真空室放入磁场中。在弧光灯的照射下，他测量了吸收光谱并发现某些特定的谱线出现了加宽的现象，他把这归因于被吸收光线的频率的改变。塞曼特别提到，有场存在时发射出来的光的偏振与洛伦兹预言的一样，是由原子内带电粒子的圆周运动产生的。他估计这些粒子的荷质比约为 10^7 。

[英文](#)

我在对克尔磁光效应进行测量时突然产生了这样的想法：当磁力作用于火焰时，火焰发射出的光的周期是否会发生变化。结果证实这样的作用确实存在。我把浸泡在普通食盐中的石棉丝放在置于鲁姆科夫电磁体两极之间的氢氧焰中。火焰光用罗兰光栅检验。每当电路接通时都能看到两条D线的加宽。

[英文](#)

鉴于也许有人会将谱线加宽归因于磁场对火焰的某种已知作用使钠蒸气的密度和温度发生了变化，我已采用了更加没有异议的实验方法进行了确证。

[英文](#)

我们在素瓷管（与普林斯海姆在他著名的气体辐射实验中所用的一样）内对钠进行高温加热。管的两端用两块相互平行的平玻璃板密封，其有效区域为1厘米。该管被水平地置于两极之间，与磁力线垂直。弧光灯的光穿过其中，吸收光谱中显示出两条D线。管子不停地绕着它的轴自转以保持各处温度均衡，磁作用使谱线迅速加宽。很可能是因为钠光的周期在磁场中发生了变化。值得注意的是，这方面第一个有记录的实验是法拉第早在1862年进行的，那时的资源并不完备，得到的是阴性的结果（麦克斯韦，《文集》，第2卷，第790页）。

[英文](#)

前面已经介绍了我对谱线磁化进行研究的起因。周期变化的可能性使我首先想到的是原子与麦克斯韦分子涡旋之间的加速和减速作用力；然后想到的是开尔文勋爵提出的一个快速旋转体系与双摆复合体的例子。然而，使我受到启发并最终得出正确结论的是洛仑兹教授提出的关于电现象的理论。 [英文](#)

这个理论认为：在所有物体中，都存在小的、带电的分子单元，所有电的过程都与这些“离子”的平衡或运动有关。在我看来，只要认为在磁场中力直接作用于这些离子上，就足以解释这些现象。 [英文](#)

我向洛仑兹教授阐述了我的观点，他友好地告诉我离子如何运动也许是可以计算的，并进一步建议说，如果我对该理论的应用是正确的，那么就会出现以下结果：当沿磁力线方向观察时，从加宽谱线边缘发出的光应该是圆偏振光；此外，这个效应的大小将能使人们测定离子所带电荷与其质量的比值。我们可以用 e/m 表示这个比值。后来我用四分之一波片和检偏器测量发现，当观测方向与磁力线一致时，磁场加宽谱线的边缘果然是圆偏振的。粗略的测定表明，如果用 e 来表示电磁单位， e/m 这一比值的数量级大约为 10^7 。 [英文](#)

反之，如果观察火焰的方向与磁力线垂直，加宽的钠线边缘出现的是平面偏振光，这与理论相符。这些都是离子存在的直接证据。 [英文](#)

这项研究是在莱顿大学物理研究所进行的，不久之后研究报告将刊登在《莱顿大学学报》上。 [英文](#)

非常感谢昂内斯教授对我的工作的重视。 [英文](#)

（沈乃澂 翻译；赵见高 审稿）

* 由阿瑟·斯坦顿翻译自《柏林物理学会会刊》。

Intra-atomic Charge

F. Soddy

What was the internal structure of an atom? While Ernest Rutherford's experiments in 1911 had convinced him that the atom contained a dense, positively charged nucleus, others were not so sure. Here Rutherford's sometime collaborator Frederick Soddy suggested that the nucleus must also contain negative charges, expelled during so-called radioactive beta decay. Soddy introduces the term "isotope": atoms essentially identical in their chemical properties but with differing nuclei. For any given nuclear charge, he asserted, an atom may have any number of electrons in an "outer ring system". Changes in this number are a consequence of chemical action, with no effect on the nucleus. Clarification of this view awaited the discovery of the proton and neutron. [中文](#)

THAT the intra-atomic charge of an element is determined by its place in the periodic table rather than by its atomic weight, as concluded by A. van der Broek (*Nature*, November 27, p. 372), is strongly supported by the recent generalisation as to the radio-elements and the periodic law. The successive expulsion of one α and two β particles in three radio-active changes in any order brings the intra-atomic charge of the element back to its initial value, and the element back to its original place in the table, though its atomic mass is reduced by four units. We have recently obtained something like a

direct proof of van der Broek's view that the intra-atomic charge of the nucleus of an atom is not a purely positive charge, as on Rutherford's tentative theory, but is the difference between a positive and a smaller negative charge. [中文](#)

Fajans, in his paper on the periodic law generalisation (*Physikal. Zeitsch.*, 1913, vol. XIV, p. 131), directed attention to the fact that the changes of chemical nature consequent upon the expulsion of α and β particles are precisely of the same kind as in ordinary electrochemical changes of valency. He drew from this the conclusion that radio-active changes must occur in the same region of atomic structure as ordinary chemical changes, rather than with a distinct inner region of structure, or "nucleus", as hitherto supposed. In my paper on the same generalisation, published immediately after that of Fajans (*Chem. News*, February 28), I laid stress on the absolute identity of chemical properties of different elements occupying the same place in the periodic table. [中文](#)

A simple deduction from this view supplied me with a means of testing the correctness of Fajans's conclusion that radio-changes and chemical changes are concerned with the same region of atomic structure. On my view his conclusion would involve nothing else than that, for example, uranium in its tetravalent uranous compounds must be chemically identical with and non-separable from thorium compounds. For uranium X, formed from uranium I by expulsion of an α particle, is chemically identical with thorium, as also is ionium formed in the same way from uranium II. Uranium X loses two β particles and passes back into uranium II, chemically identical with uranium. Uranous salts also lose two electrons and pass into the more common hexavalent uranyl compounds. If these electrons come from the same region of the atom uranous salts should be chemically non-separable from thorium salts. But they are not. [中文](#)

There is a strong resemblance in chemical character between uranous

and thorium salts, and I asked Mr. Fleck to examine whether they could be separated by chemical methods when mixed, the uranium being kept unchanged throughout in the uranous or tetravalent condition. Mr. Fleck will publish the experiments separately, and I am indebted to him for the result that the two classes of compounds can readily be separated by fractionation methods. [中文](#)

This, I think, amounts to a proof that the electrons expelled as β rays come from a nucleus not capable of supplying electrons to or withdrawing them from the ring, though this ring is capable of gaining or losing electrons from the exterior during ordinary electrochemical changes of valency. [中文](#)

I regard van der Broek's view, that the number representing the net positive charge of the nucleus is the number of the place which the element occupies in the periodic table when all the possible places from hydrogen to uranium are arranged in sequence, as practically proved so far as the relative value of the charge for the members of the end of the sequence, from thallium to uranium, is concerned. We are left uncertain as to the absolute value of the charge, because of the doubt regarding the exact number of rare-earth elements that exist. If we assume that all of these are known, the value for the positive charge of the nucleus of the uranium atom is about 90. Whereas if we make the more doubtful assumption that the periodic table runs regularly, as regards numbers of places, through the rare-earth group, and that between barium and radium, for example, two complete long periods exist, the number is 96. In either case it is appreciably less than 120, the number were the charge equal to one-half the atomic weight, as it would be if the nucleus were made out of α particles only. Six nuclear electrons are known to exist in the uranium atom, which expels in its changes six β rays. Were the nucleus made up of α particles there must be thirty or twenty-four respectively nuclear electrons, compared with ninety-six or 102 respectively in the ring. If,

as has been suggested, hydrogen is a second component of atomic structure, there must be more than this. But there can be no doubt that there must be some, and that the central charge of the atom on Rutherford's theory cannot be a pure positive charge, but must contain electrons, as van der Broek concludes. [中文](#)

So far as I personally am concerned, this has resulted in a great clarification of my ideas, and it may be helpful to others, though no doubt there is little originality in it. The same algebraic sum of the positive and negative charges in the nucleus, when the arithmetical sum is different, gives what I call "isotopes" or "isotopic elements", because they occupy the same place in the periodic table. They are chemically identical, and save only as regards the relatively few physical properties which depend upon atomic mass directly, physically identical also. Unit changes of this nuclear charge, so reckoned algebraically, give the successive places in the periodic table. For any one "place," or any one nuclear charge, more than one number of electrons in the outer-ring system may exist, and in such a case the element exhibits variable valency. But such changes of number, or of valency, concern only the ring and its external environment. There is no in- and out-going of electrons between ring and nucleus. [中文](#)

(92, 399-400; 1913)

Frederick Soddy: Physical Chemistry Laboratory, University of Glasgow.

原子内的电荷

索迪

原子的内部结构是怎样的？1911年，当欧内斯特·卢瑟福用实验验证了原子包含一个致密的带正电的核时，其他人并没有表示十分肯定。在这篇文章中，曾经与卢瑟福合作过的弗雷德里克·索迪提出原子核中必须同时也包含负电荷，这些负电荷会在放射性 β 衰变时发射出去。索迪引入了“同位素”的概念，即原子核结构不同但化学性质基本一致的原子。他认为，对于任意给定的核电荷，原子“外层系统”可以排布任意的电子数量。化学反应能引起外层电子数的变化，但对原子核没有影响。后来质子和中子的发现证实了他的观点。

[英文](#)

范德布鲁克断言（《自然》，11月27日，第372页），一种元素原子内的电荷是由它在周期表中的位置而不是它的原子量确定的，这一论断受到最近一些关于放射性元素与周期律的结论的强力支持。如果在3次放射性变化中相继发射出1个 α 粒子和2个 β 粒子，那么不管这3次衰变的次序如何，都会使该元素的原子内电荷回到初始数值，元素也回到了它在周期表中的原始位置，但是它的原子质量却减少了4个单位。最近我们获得了一些证据，能够直接支持范德布鲁克的观点：就像卢瑟福的初步理论所指出的，原子核内的电荷并不是单纯的正电荷，而是正电荷与较小的负电荷的差值。

[英文](#)

法扬斯在他那篇关于周期律的一般法则的论文（《物理学杂志》，1913年，第14卷，第131页）中，特别指出了如下事实：由于 α 粒子和 β 粒子的发射而引起的元素化学性质的改变，与普通的会发生价态变动的由电化学变化引起的物质化学性质的改变完全属于同一类型。他由此得出的结论是，放射性变化必定与普通的化学变化一样发生在原子结构的

同一区域，而不是像我们目前所假设的——放射性变化发生在被称为“核”的一个完全不同的内部区域。在法扬斯的论文发表后不久，我也针对同一主题发表了一篇论文（《化学新闻》，2月28日），文中我将重点放在了周期表中处于同一位置的不同元素具有完全相同的化学性质这一点上。 [英文](#)

此观点的一个简单推论为我提供了一种检验法扬斯认为的放射性变化与化学变化发生于原子结构中同一区域这一观点是否正确的方法。我认为，他的结论其实就是下面的意思：举例来说，铀的四价化合物中的铀元素必定与钍化合物中的钍元素具有完全相同的化学性质且不可区分。因为，由铀I发射1个 α 粒子而形成的铀X与钍，以及由铀II以同样方式形成的“镭”，在化学性质上是一致的。铀X发射2个 β 粒子就又回到铀II，铀II与铀的化学性质是一致的。亚铀盐也可以失去2个电子并形成更为常见的六价铀的化合物。如果这些电子来自原子中的同一区域，那么亚铀盐和钍盐应该具有相同的化学性质并且不可区分。然而事实并非如此。 [英文](#)

亚铀盐与钍盐的化学性质非常相似，我已经请弗莱克先生研究是否可以在始终保持铀元素的四价或六价状态不发生改变的前提下用化学方法将铀盐与钍盐的混合物中的铀和钍分离开来。弗莱克先生将独立发表他的实验，我很感激能够使用他取得的结果，即通过分馏的方法可以很顺利地分离这两类化合物。 [英文](#)

我认为这足以证明，以 β 射线形式发射出的电子来自核，尽管核无法为核外圈层提供电子或从中取走电子，但核外圈层可以在普通的会发生价态变动的电化学变化中从外部获取电子或失去电子。 [英文](#)

在研究从铊到铀这些处在周期表序列尾部的成员的电荷相对值时，我把范德布鲁克的观点当作是已经被证实的，即从氢到铀按顺序排好周期表中所有可能的位置后，代表核所具有的净正电荷的数值就正好是元素在周期表中所处位置对应的数值。不过我们仍旧不能确定电荷的绝对值，因为对到底存在多少种稀土元素还存在疑问。如果我们假定这些都是已知的，那么铀原子核中正电荷的数值大约是90。如果我们采取另一个更不确定的假设，即从周期表中位置对应的数值的角度来看，包括全

部稀土元素以及介于钷与镱之间的元素在内的周期表是规则排布的，整个周期表有两个完整的长周期，这样得到的数值就会是96。不管是哪种情况，该数值都明显小于120，即便假设其电荷数值就是120，那也只是其原子量的一半，如果真是这样，那核可能就只有 α 粒子了。已知铀原子中存在6个核电子，在放射性变化中这些核电子以6次 β 射线的形式发射出来。如果核是由 α 粒子构成的话，那么与核外圈层中具有96个或者102个电子相对应，就必须有30个或者24个核电子。另外已经有人提出氢是原子结构的另一种构件，如果考虑上这一点的话，那么其核电子数就不止于此了。但是有一点毋庸置疑，那就是必定存在一些核电子，而且卢瑟福理论中原子的中心电荷也不是单纯的正电荷，而是必定包含负电子，就像范德布鲁克断定的那样。 英文

就目前我个人的思考结果来说，以上是对我的观点的一个很明晰的解释。虽然很明显其中并无多少创见，但也许会对其他人有所帮助吧。根据核内正负电荷的代数和相同而算数和不同的现象，我提出了“同位素”或“同位置元素”的概念，因为它们在周期表中处于相同的位置。它们在化学性质上是完全相同的，除了很有限的一些直接决定于原子量的物理性质外，其他大部分物理性质也是完全相同的。从数学角度来看，核电荷数会单位递增地发生变化，这使得周期表中的位置也连续地变化。对于周期表中任意一个位置，或者说任意一个确定的核电荷数，可以存在不止一种外层电子数，在这种情况下元素就表现出了不同的价态。不过，这种电子数或者价态的变化只是考虑了核外圈层及其外部环境，并没有把核外圈层与核之间的电子进出过程考虑进去。 英文

（王耀杨 翻译；汪长征 审稿）

The Structure of the Atom

E. Rutherford

Responding to a comment by Frederick Soddy, Ernest Rutherford here clarifies his view on the structure of the atomic nucleus. Soddy had suggested that Rutherford believed the nucleus to contain positive charges only. On the contrary, Rutherford insists, he believes only that the atomic nucleus is small, dense, and positively charged overall. Moreover, he thinks that two of the key products of radioactive decay—alpha and beta particles—might both originate from the nucleus. Rutherford supports a recent suggestion that the charge on the atomic nucleus is equal to the atomic number, and not to half the atomic weight. This observation prefigured the revelation that the atomic number is the equal to the number of protons in the nucleus.

中文

IN a letter to this journal last week, Mr. Soddy has discussed the bearing of my theory of the nucleus atom on radio-active phenomena, and seems to be under the impression that I hold the view that the nucleus must consist entirely of positive electricity. As a matter of fact, I have not discussed in any detail the question of the constitution of the nucleus beyond the statement that it must have a resultant positive charge. There appears to me no doubt that the α particle does arise from the nucleus, and I have thought for some time that the evidence points to the conclusion that the β particle has a similar

origin. This point has been discussed in some detail in a recent paper by Bohr (*Phil. Mag.*, September, 1913). The strongest evidence in support of this view is, to my mind, (1) that the β ray, like the α ray, transformations are independent of physical and chemical conditions, and (2) that the energy emitted in the form of β and γ rays by the transformation of an atom of radium C is much greater than could be expected to be stored up in the external electronic system. At the same time, I think it very likely that a considerable fraction of the β rays which are expelled from radio-active substances arise from the external electrons. This, however, is probably a secondary effect resulting from the primary expulsion of a β particle from the nucleus.

中文

The original suggestion of van der Broek that the charge on the nucleus is equal to the atomic number and not to half the atomic weight seems to me very promising. This idea has already been used by Bohr in his theory of the constitution of atoms. The strongest and most convincing evidence in support of this hypothesis will be found in a paper by Moseley in *The Philosophical Magazine* of this month. He there shows that the frequency of the X radiations from a number of elements can be simply explained if the number of unit charges on the nucleus is equal to the atomic number. It would appear that the charge on the nucleus is the fundamental constant which determines the physical and chemical properties of the atom, while the atomic weight, although it approximately follows the order of the nucleus charge, is probably a complicated function of the latter depending on the detailed structure of the nucleus.

中文

(92, 423; 1913)

原子结构

卢瑟福

为了回应弗雷德里克·索迪的意见，欧内斯特·卢瑟福在这篇文章中进一步解释了他对原子核结构的观点。索迪曾指出卢瑟福认为原子核只包含正电荷，而卢瑟福却强调说他只承认原子核很小、很致密，以及整体带正电。此外，卢瑟福认为，放射性衰变的两个主要产物，即 α 粒子和 β 粒子，可能都源自原子核。卢瑟福同意最近有人提出的关于核电荷等于原子序数而非原子量的一半的观点。这个结果预示了原子序数与原子核中的质子数相等这一关系。 [英文](#)

在上周致贵刊的一封信中，索迪先生对我关于放射性现象中原子核的理论进行了相关讨论，他似乎以为，我认定原子核必须完全由带正电荷的粒子构成。事实上，我只是认为原子核必定具有总和为正的电荷，而对它的具体构成并未发表看法。在我看来， α 粒子无疑是产生于核的，而且经过一段时间的思考，我认为有证据表明 β 粒子也源自核。玻尔在最近的一篇论文（《哲学杂志》，1913年9月）中对这一点进行了较为详细的讨论。支持这一观点的最强有力的证据是：（1）与 α 射线一样， β 射线的衰变也是与物理和化学条件无关的；（2）镭原子发生衰变时以 β 射线或 γ 射线的形式放出的能量C，比预想的外部电子系统所存储的能量大得多。不过，放射性物质发射出的 β 射线可能有相当一部分来源于外部电子。这也许是原子核中的 β 粒子的初级辐射引起的一种次级效应。 [英文](#)

范德布鲁克最先提出，核所带的基本电荷数应等于原子序数而不是原子量的一半，我认为这是非常有可能的。玻尔在他的原子结构理论中已经应用了这种观点。在莫塞莱本月发表于《哲学杂志》上的文章中，可以找到支持这个假说的最强有力也最令人信服的证据。文中表明，如

果核所带的基本电荷数等于原子序数，就能方便地对多种元素所发出的X辐射的频率进行解释。看起来，核所带的基本电荷数是确定原子物理和化学性质的基本常数，尽管原子量的顺序与相应原子核电荷数的顺序基本一致，但原子量并非如人们以前所设想的那样是其核电荷数的两倍，可能是核电荷数的复杂函数，其函数关系与核的具体结构有关。

英文

（王耀杨 翻译；鲍重光 审稿）

The Reflection of X-rays

The German physicist Max von Laue demonstrated the phenomenon of X-ray diffraction in 1912. This high-energy form of light, with wavelengths comparable to the spacing between molecules in crystalline solids, could be used to reveal crystal structures. Other physicists had deduced the relationship between the lattice spacing and the angles at which bright diffraction spots should occur. Here Maurice de Broglie, the brother of physicist Louis de Broglie, introduces what came to be known as the rotating-crystal method for recording X-ray diffraction from a single crystal. The technique detects X-rays reflected along the surface of a series of so-called “Laue cones”. It became the standard method of X-ray diffraction for many years. [中文](#)

IN view of the great interest of Prof. Bragg’s and Messrs. Moseley and Darwin’s researches on the distribution of the intensity of the primary radiation from X-ray tubes, it may be of interest to describe an alternate method which I have found very convenient (*Comptes rendus*, November 17, 1913). [中文](#)

As we know, the wavelength of the reflected ray is defined by the equation $n\lambda = 2d\sin\theta$, where n is a whole number, d the distance of two parallel planes, and θ the glancing angle. If one mounts a crystal with one face in the axis of an instrument that turns slowly and regularly, such as, for instance, a registering barometer, the angle changes gradually and continuously. [中文](#)

If, therefore, one lets a pencil of X-rays, emerging from a slit, be reflected from this face on to a photographic plate, one finds the true spectrum of the X-rays on the plate, supposing intensity of the primary beam to have remained constant. (This can be tested by moving another plate slowly before the primary beam during the exposure.)

中文

The spectra thus obtained are exactly analogous to those obtained with a diffraction grating, and remind one strongly of the usual visual spectra containing continuous parts, bands, and lines. 中文

So far I have only identified the doublet, $11^{\circ}17'$ and $11^{\circ}38'$, described by Messrs. Moseley and Darwin. The spectra contain also a number of bright lines about two octaves shorter than these, and the continuous spectrum is contained within about the same limits. These numbers may be used in the interpretations of diffraction Röntgen patterns, as they were obtained with tubes of the same hardness as those used for producing these latter. 中文

The arrangement described above enables us to distinguish easily the spectra of different orders, as the interposition of an absorbing layer cuts out the soft rays, but does not weaken appreciably the hard rays of the second and higher orders. 中文

It is convenient also for absorption experiments; thus a piece of platinum foil of 0.2 mm thickness showed transparent bands. The exact measurements will be published shortly, as well as the result of some experiments I am engaged upon at present upon the effect of changing the temperature of the crystal. 中文

Maurice de Broglie

* * *

As W. L. Bragg first showed, when a beam of soft X-rays is incident on

a cleavage plane of mica, a well-defined proportion of the beam suffers a reflection strictly in accordance with optical laws. In addition to this generally reflected beam, Bragg has shown that for certain angles of incidence, there occurs a kind of selective reflection due to reinforcement between beams incident at these angles on successive parallel layers of atoms. [中文](#)

Experiments I am completing seem to show that a generally reflected beam of rays on incidence at a second crystal surface again suffers optical reflection; but the degree of reflection is dependent on the orientation of this second reflector relative to the first. [中文](#)

The method is a photographic one. The second reflector is mounted on a suitably adapted goniometer, and the photographic plate is mounted immediately behind the crystal. The beam is a pencil 1.5 mm in diameter. When the two reflectors are parallel the impression on the plate, due to the two reflections, is clear. But as the second reflector is rotated about an axis given by the reflected beam from the first and fixed reflector, the optically reflected radiation from the second reflector—other conditions remaining constant—diminishes very appreciably. As the angle between the reflectors is increased from 0° to 90° , the impression recorded on the photographic plate diminishes in intensity. For an angle of 20° it is still clear; for angles in the neighbourhood of 50° it is not always detectable; and for an angle of 90° it is very rarely detectable in the first stages of developing, and is then so faint that it never appears on the finished print. [中文](#)

These results, then, would show that the generally reflected beam of X-rays is appreciably polarised in a way exactly analogous to that of ordinary light. Owing to the rapidity with which the intensity of the generally reflected beam falls off with the angle of incidence of the primary beam, it has not been possible to work with any definiteness with angles of incidence greater than about 78° , and this is unfortunately a considerably larger angle than the probable polarising

angle. Experiments with incidence in the neighbourhood of 45° should prove peculiarly decisive, for whereas ordinary light cannot as a rule be completely polarised by reflection, the reflection of X-rays, which occurs at planes of atoms, is independent of any contamination of the exposed crystal surface, and polarisation, once established, should prove complete for radiation reflected at the polarising angle. The selectively reflected X-rays seem to show the same effects as does the generally reflected beam. Selectively reflected radiation is always detectable after the second reflection, but this seems due to the selectively reflected radiation produced at the second reflector by the unpolarised portion of the beam generally reflected at the first reflector. 中文

The application of a theory of polarisation to explain the above results is interestingly supported by the fact that in the case of two reflections by parallel reflectors, the proportion of X-rays reflected at the second reflector is invariably greater than the proportion of rays reflected at the first; that is, the ratio of reflected radiation to incident radiation at the second reflector is always greater than the same ratio at the first reflector. This might be expected if vibrations perpendicular to the plane of incidence are to be reflected to a greater extent than those in the plane of incidence. The proportion of such vibrations is larger in the beam incident on the second reflector than in the original beam, and a greater proportion of radiation would be reflected at the second reflector than could be at the first. For the case of parallel reflectors and incidence of a primary beam on the first at the polarising angle, the reflection at the second should be complete. 中文

E. Jacot

(92, 423-424; 1913)

Maurice de Broglie: 29, Rue Chateaubriand, Paris, December 1.

E. Jacot: South African College, Cape Town, November 14.

X射线的反射

1912年，德国物理学家马克斯·冯·劳厄证明了X射线的衍射现象。这种形式的光能量很高，其波长与晶格中分子之间的距离相近，因而可以用于研究晶体的结构。其他物理学家推算出了晶格间距与预计会出现明亮衍射斑点的角度之间的关系。在这篇文章中，物理学家路易斯·德布罗意的哥哥莫里斯·德布罗意介绍了记录单晶X射线衍射的方法，后来被称作旋转晶体法。该技术探测沿着一组被称作“劳厄锥”的晶面反射的X射线。许多年来这种方法一直是人们研究X射线衍射的标准方法。 [英文](#)

鉴于大家对布拉格教授、莫塞莱先生以及达尔文先生关于从X射线管发射的初级辐射强度分布的研究有极大的兴趣，我已发现的另一种很方便的方法可能也会引起大家的兴趣（《法国科学院院刊》，1913年11月17日）。 [英文](#)

如我们所知，反射射线的波长由方程 $n\lambda = 2d\sin\theta$ 确定，式中 n 是一个整数， d 是两个平行平面间的距离， θ 是掠射角。如果我们将一块晶体放在一台缓慢而有规律旋转的仪器（例如，记录式气压计）上，使晶体的一个表面沿仪器的轴向，那么反射的角度将连续不断地发生变化。

[英文](#)

如果我们使一束X射线从狭缝中射出，并被此晶面反射到照相干版上，假定初级光束的强度保持不变，即可在干版上得到X射线的真实光谱。（可以通过曝光时在初级光束前方缓慢移动另一块照相干版来检验光束强度是否保持不变。） [英文](#)

这样得到的光谱与用衍射光栅得到的光谱非常类似，而且很容易使人想起那些含有连续区、谱带和谱线的普通可见光谱。 [英文](#)

至今，我仅确认了莫塞莱先生和达尔文先生所描述的双线： $11^{\circ}17'$ 和 $11^{\circ}38'$ 。这个光谱还包含比双线短大约两个倍频程的许多亮线，还有在大致相同范围内的连续谱。这些光谱线也许可用于解释伦琴的衍射图样，因为产生伦琴的衍射图样时使用的管子与产生这些谱线时使用的管子具有相同的硬度。 [英文](#)

上述装置能使我们很容易地区别不同级的谱线，因为插入吸收层可以截断软射线，但并不会太明显地减弱次级和更高级的硬射线。 [英文](#)

进行吸收实验也是很方便的。用这样的方法，一片0.2毫米厚的铂箔会显示出透射带。至于确切的测量方法以及目前我在改变晶体温度方面所做的实验得到的结果，都将在我即将发表的文章中进行介绍。 [英文](#)

莫里斯·德布罗意

* * *

正如布拉格首先指出的，当一束软X射线入射到云母的一个解理面上时，光束反射部分所占的比例严格遵照光学定律。除了这种普通的反射光束，布拉格指出，对于特定的入射角，由于以这些角度入射到原子中连续的平行层上的光束彼此相互增强，因而会产生一种选择性的反射。 [英文](#)

我正在进行的实验似乎表明，当一个普通的反射束入射到下一个晶体表面上时，还会再次产生光学反射，但是，反射的程度取决于第二个反射面与第一个反射面之间的夹角。 [英文](#)

我用的是照相记录法。第二个反射面被安装在调整好的测角仪上，照相干版紧贴在晶体后面。光束直径为1.5毫米。当两个反射面平行时，两次反射在照相干版上产生的影像是清晰的。但是，当以第一个固定反射面上反射的射线为轴旋转第二个反射面时，假如其他条件不变，则从第二个反射面上反射的光学辐射明显减弱。当反射面之间的夹角从 0° 增加到 90° 时，照相干版上记录的影像的清晰度不断降低。在角度为 20°

时，影像仍然很清晰；角度为 50° 左右时，经常检测不到影像；角度为 90° 时，由于影像非常微弱，在第一步显影阶段已经很难看到，而在最终冲洗出的照片上则从来没有出现过。 [英文](#)

以上结果表明，X射线普通反射束的偏振特性在某种程度上完全类似于普通光的偏振。由于普通反射束的强度随着初级光束入射角的增加而迅速下降，当入射角超过 78° 后就很难得到确定无疑的影像了。遗憾的是，这个角度比可能的偏振角大很多。入射角在 45° 附近的实验尤其具有决定意义，虽然通常不能通过反射使普通光完全偏振，但在原子平面上X射线的反射并不受被辐照的晶体表面上任何污染的影响，一旦出现偏振，那么偏振角处被反射的辐射将是完全偏振的。被选择性反射的X射线与普通的反射有相同的效应。在第二次反射后总能检测到被选择性反射的辐射，但这似乎是由第一个反射面处被反射的那部分非偏振辐射在第二个反射面上发生选择性反射而造成的。 [英文](#)

偏振理论可以用来解释上述结果，这得到了以下事实的强烈支持，在由两个平行反射面引起的两次反射中，第二个反射面上被反射的X射线总是多于第一个反射面上被反射的X射线；即在第二个反射面上被反射的辐射相对于入射辐射的比例，总是大于第一个反射面。这就可以预期，垂直于入射平面的振动被反射的量比在入射平面内的振动更大。与原光束相比，入射到第二个反射面上的光束中垂直于入射平面的振动所占比例更大一些，因此在第二个反射面上被反射的辐射的比例大于第一个反射面。在两个反射面相互平行的情况下，如果初始光束以偏振角入射到第一个反射面上，则在第二个反射面上它将被完全反射。 [英文](#)

贾科

（沈乃澂 翻译；江丕栋 审稿）

Einstein's Relativity Theory of Gravitation

E. Cunningham

Arthur Eddington had recently announced his measurements of the deflection of starlight during a solar eclipse, in apparent agreement with Einstein's general theory of relativity. Here Ebenezer Cunningham surveys Einstein's ideas. Einstein's 1905 work had established a link between inertia and energy, and his new work pursued the question of whether gravity too might be linked to energy. What emerges from the theory, Cunningham argues, is a view in which there is no ultimate criterion for the equality of space or time intervals, but only the equivalence of an infinite number of ways of mapping out physical events. All this has been made possible, he notes, by Einstein adopting mathematics already developed by Riemann, Levi-Civita and others. [中文](#)

I

THE results of the Solar Eclipse Expeditions announced at the joint meeting of the Royal Society and Royal Astronomical Society on November 6 brought for the first time to the notice of the general public the consummation of Einstein's new theory of gravitation. The theory was already in being before the war; it is one of the few pieces of pure scientific knowledge which have not been set aside in the

emergency; preparations for this expedition were in progress before the war had ceased. [中文](#)

Before attempting to understand the theory which, if we are to believe the daily Press, has dimmed the fame of Newton, it may be worth while to recall what it was that he did. It was not so much that he, first among men, used the differential calculus. That claim was disputed by Leibniz. Nor did he first conceive the exact relations of inertia and force. Of these, Galileo certainly had an inkling. Kepler, long before, had a vague suspicion of a universal gravitation, and the law of the inverse square had, at any rate, been mooted by Hooke before the “Principia” saw the light. The outstanding feature of Newton’s work was that it drew together so many loose threads. It unified phenomena so diverse as the planetary motions, exactly described by Kepler, the everyday facts of falling bodies, the rise and fall of the tides, the top-like motion of the earth’s axis, besides many minor irregularities in lunar and planetary motions. With all these drawn into such a simple scheme as the three laws of motion combined with the compact law of the inverse square, it is no wonder that flights of speculation ceased for a time. The universe seemed simple and satisfying. For a century at least there was little to do but formal development of Newton’s dynamics. In the mid-eighteenth century Maupertuis hinted at a new physical doctrine. He was not content to think of the universe as a great clock the wheels of which turned inevitably and irrevocably according to a fixed rule. Surely there must be some purpose, some divine economy in all its motions. So he propounded a principle of least action. But it soon appeared that this was only Newton’s laws in a new guise; and so the eighteenth century closed. [中文](#)

The nineteenth saw great changes. When it closed, the age of electricity had come. Men were peering into the secrets of the atom. Space was no longer a mighty vacuum in the cold emptiness of which

rolled the planets. It was filled in every part with restless energy. Ether, not matter, was the last reality. Mass and matter were electrical at bottom. A great problem was set for the present generation: to reconcile one with the other the new laws of electricity and the classical dynamics of Newton. At this point the principle of least action began to assume greater importance; for the old and the new schemes of the universe had this in common, that in each of them the time average of the difference between the kinetic and the potential energies appears to be a minimum. 中文

One of the main difficulties encountered by the electrical theory of matter has been the obstinate refusal of gravitation to come within its scope. Quietly obeying the law of the inverse square, it heeded not the bustle and excitement of the new physics of the atom, but remained, independent and inevitable, a constant challenge to rash claimants to the key of the universe. The electrical theory seemed on the way to explain every property of matter yet known, except the one most universal of them all. It could trace to its origins the difference between copper and glass, but not the common fact of their weight; and now the ether began silently to steal away. 中文

One matter that has seriously troubled men in Newton's picture of the universe is its failure to accord with the philosophic doctrine of the relativity of space and time. The vital quantity in dynamics is the acceleration, the change of motion of a body. This does not mean that Newton assumed the existence of some ultimate framework in space relative to which the actual velocity of a body can be uniquely specified, for no difference is made to his laws if any arbitrary constant velocity is added to the velocity of every particle of matter at all time. The serious matter is that the laws cannot possibly have the same simplicity of form relative to two frameworks of which one is in rotation or non-uniform motion relative to the other. It seems, for instance, that if Newton were right, the term "fixed direction" in space

means something, but “fixed position” means nothing. It seems as if the two must stand or fall together. And yet the physical relations certainly make a distinction. Why this should be so has not yet been made known to us. Whatever new theory we adopt must take account of the fact. 中文

It was with some feeling of relief that men hailed the advent of the ether as a substitute for empty space, though we may note in passing that some philosophers—Comte, for example—have held that the concept of an ether, infinite and intangible, is as illogical as that of an absolute space. But, jumping at the notion, physicists proposed to measure all velocities and rotations relative to it. Alas! the ether refused to disclose the measurements. Explanations were soon forthcoming to account for its reluctance; but these were so far-reaching that they explained away the ether itself in the sense in which it was commonly understood. At any rate, they proved that this creature of the scientific imagination was not one, but many. It quite failed to satisfy the cravings for a permanent standard against which motion might be measured. The problem was left exactly where it was before. This was prewar relativity, summarised by Einstein in 1905. The physicists complained loudly that he was taking away their ether.

中文

Let it not be thought, however, that the results of the hypothesis then advanced were purely negative. They showed quite clearly that many current ideas must be modified, and in what direction this must be done. Most notably it emphasised the fact that inertia is not a fundamental and invariable property of matter; rather it must be supposed that it is consequent upon the property of energy. And, again, energy is a relative term. One absolute quantity alone remained; one only stood independent of the taste or fancy of the observer, and that was “action”. While the ether and the associated system of measurement could be selected as any one of a legion, the

principle of least action was satisfied in each of them, and the magnitude of the action was the same in all. [中文](#)

But, still, gravitation had to be left out; and the question from which Einstein began the great advance now consummated in success was this. If energy and inertia are inseparable, may not gravitation, too, be rooted in energy? If the energy in a beam of light has momentum, may it not also have weight? [中文](#)

The mere thought was revolutionary, crude though it be. For if at all possible it means reconsidering the hypothesis of the constancy and universality of the velocity of light. This hypothesis was essential to the yet infant principle of relativity. But if called in question, if the velocity of light is only approximately constant because of our ordinary ways of measuring, the principle of relativity, general as it is, becomes itself an approximation. But to what? It can only be to something more general still. Is it possible to maintain anything at all of the principle with that essential limitation removed? [中文](#)

Here was exactly the point at which philosophers had criticised the original work of Einstein. For the physicist it did too much. For the philosopher it was not nearly drastic enough. He asked for an out-and-out relativity of space and time. He would have it that there is no ultimate criterion of the equality of space intervals or time intervals, save complete coincidence. All that is asked is that the order in which an observer perceives occurrences to happen and objects to be arranged shall not be disturbed. Subject to this, any way of measuring will do. The globe may be mapped on a Mercator projection, a gnomonic, a stereographic, or any other projection; but no one can say that one is a truer map than another. Each is a safe guide to the mariner or the aviator. So there are many ways of mapping out the sequences of events in space and time, all of which are equally true pictures and equally faithful servants. [中文](#)

This, then, was the mathematical problem presented to Einstein and solved. The pure mathematics required was already in existence. An absolute differential calculus, the theory of differential invariants, was already known. In pages of pure mathematics that the majority must always take as read, Riemann, Christoffel, Ricci, and Levi-Civita supplied him with the necessary machinery. It remained out of their equations and expressions to select some which had the nearest kinship to those of mathematical physics and to see what could be done with them. [中文](#)

(104, 354-356; 1919)

II. The Nature of the Theory

In the first article an attempt was made to show the roads which led to Einstein's adventure of thought. On the physical side briefly it was this. Newton associated gravitation definitely with mass. Electromagnetic theory showed that the mass of a body is not a definite and invariable quantity inherent in matter alone. The energy of light and heat certainly has inertia. Is it, then, also susceptible to gravitation, and, if so, exactly in what manner? The very precise experiments of Eötvös rather indicated that the mass of a body, as indicated by its inertia, is the same as that which is affected by gravitation. [中文](#)

Also, how must the expression of Newton's law of gravitation be modified to meet the new view of mass? How, also, must the electromagnetic theory and the related pre-war relativity be adapted to allow of the effect of gravitation? With the relaxation of the stipulation that the velocity of light shall be constant, will the principle of relativity become more general and acceptable to the philosophic doctrine of relativity, or will it, on the other hand, become completely impossible? [中文](#)

One point arises immediately. The out-and-out relativist will not admit an absolute measure of acceleration any more than of velocity. The effect, however, of an accelerated motion is to produce an apparent change in gravitation; the measure of gravitation at any place must therefore be a relative quantity depending upon the choice which the observer makes as to the way in which he will measure velocities and accelerations. This is one of Einstein's fundamental points. It has been customary in expositions of mechanics to distinguish between so-called "centrifugal force" and "gravitational force". The former is said to be fictitious, being simply a manifestation of the desire of a body to travel uniformly in a straight line. On the other hand, gravitation has been called a real force because associated with a cause external to the body on which it acts. [中文](#)

Einstein asks us to consider the result of supposing that the distinction is not essential. This was his so-called "principle of equivalence". It led at once to the idea of a ray of light being deviated as it passes through a field of gravitational force. An observer near the surface of the earth notes objects falling away from him towards the earth. Ordinarily, he attributes this to the earth's attraction. If he falls with them, his sense of gravitation is lost. His watch ceases to press on the bottom of his pocket; his feet no longer press on his boots. To this falling observer there is no gravitation. If he had time to think or make observations of the propagation of light, according to the principle of equivalence he would now find nothing gravitational to disturb the rectilinear motion of light. In other words, a ray of light propagated horizontally would share in his vertical motion. To an observer not falling, and, therefore, cognisant of a gravitational field, the path of the ray would therefore be bending downward towards the earth. [中文](#)

The systematic working out of this idea requires, as has been remarked, considerable mathematics. All that can be attempted here is to give a faint indication of the line of attack, mainly by way of

analogy. 中文

It is no new discovery to speak of time as a fourth dimension. Every human mind has the power in some degree of looking upon a period of the history of the world as a whole. In doing this, little difference is made between intervals of time and intervals of space. The whole is laid out before him to comprehend in one glance. He can at the same time contemplate a succession of events in time, and the spatial relations of those events. He can, for instance, think simultaneously of the growth of the British Empire chronologically and territorially. He can, so to speak, draw a map, a four-dimensional map, incapable of being drawn on paper, but none the less a picture of a domain of events. 中文

Let us pursue the map analogy in the familiar two-dimensional sense. Imagine that a map of some region of the globe is drawn on some material capable of extension and distortion without physical restriction save that of the preservation of its continuity. No matter what distortion takes place, a continuous line marking a sequence of places remains continuous, and the places remain in the same order along that line. The map ceases to be any good as a record of distance travelled, but it invariably records certain facts, as, for example, that a place called London is in a region called England, and that another place called Paris cannot be reached from London without crossing a region of water. But the common characteristic of maps of correctly recording the shape of any small area is lost. 中文

The shortest path from any place on the earth's surface to any other place is along a great circle; on all the common maps, one series of great circles, the meridians, is mapped as a series of straight lines. It might seem at first sight that our extensible map might be so strained that all great circles on the earth's surface might be represented by straight lines. But, as a matter of fact, this is not so. We might represent the meridians and the great circles through a second

diameter of the earth as two sets of straight lines, but then every other great circle would be represented as a curve. 中文

The extension of this to four dimensions gives a fair idea of Einstein's basic conception. In a world free from gravitation we ordinarily conceive of free particles as being permanently at rest or moving uniformly in straight lines. We may imagine a four-dimensional map in which the history of such a particle is recorded as a straight line. If the particle is at rest, the straight line is parallel to the time axis; otherwise it is inclined to it. Now if this map be strained in any manner, the paths of particles are no longer represented as straight lines. Any person who accepts the strained map as a picture of the facts may interpret the bent paths as evidence of a "gravitational field", but this field can be explained right away as due to his particular representation, for the paths can all be made straight.

中文

But our two-dimensional analogy shows that we may conceive of cases where no amount of straining will make all the lines that record the history of free particles simultaneously straight; pure mathematics can show the precise geometrical significance of this, and can write down expressions which may serve as a measure of the deviations that cannot be removed. The necessary calculus we owe to the genius of Riemann and Christoffel. 中文

Einstein now identifies the presence of curvatures that cannot be smoothed out with the presence of matter. This means that the vanishing of certain mathematical expressions indicates the absence of matter. Thus he writes down the laws of the gravitational field in free space. On the other hand, if the expressions do not vanish, they must be equal to quantities characteristic of matter and its motion. These equalities form the expression of his law of gravitation at points where matter exists. 中文

The reader will ask: What are the quantities which enter into these equations? To this only a very insufficient answer can here be given. If, in the four-dimensional map, two neighbouring points be taken, representing what may be called two neighbouring occurrences, the actual distance between them measured in the ordinary geometrical sense has no physical meaning. If the map be strained, it will be altered, and therefore to the relativist it represents something which is not in the external world of events apart from the observer's caprice of measurement. But Einstein assumes that there is a quantity depending on the relation of the points one to the other which is invariant—that is, independent of the particular map of events. Comparing one map with another, thinking of one being strained into the other, the relative positions of the two events are altered as the strain is altered. It is assumed that the strain at any point may be specified by a number of quantities (commonly denoted g_{rs}), and the invariable quantity is a function of these and of the relative positions of the points. 中文

It is these quantities g_{rs} which characterise the gravitational field and enter into the differential equations which constitute the new law of gravitation. 中文

It is, of course, impossible to convey a precise impression of the mathematical basis of this theory in non-mathematical terms. But the main purpose of this article is to indicate its very general nature. It differs from many theories in that it is not devised to meet newly observed phenomena. It is put together to satisfy a mental craving and an obstinate philosophic questioning. It is essentially pure mathematics. The first impression on the problem being stated is that it is incapable of solution; the second of amazement that it has been carried through; and the third of surprise that it should suggest phenomena capable of experimental investigation. This last aspect and the confirmation of its anticipations will form the subject of the next

III. The Crucial Phenomena

In the article last week an attempt was made to indicate the attitude of the complete relativist to the laws which must be obeyed by gravitational matter. The present article deals with particular conclusions. [中文](#)

As Minkowski remarked in reference to Einstein's early restricted principle of relativity: "From henceforth, space by itself and time by itself do not exist; there remains only a blend of the two" ("Raum und Zeit", 1908). In this four-dimensional world that portrays all history let (x_1, x_2, x_3, x_4) be a set of coordinates. Any particular set of values attached to these coordinates marks an event. If an observer notes two events at neighbouring places at slightly different times, the corresponding points of the four-dimensional map have coordinates slightly differing one from the other. Let the differences be called (dx_1, dx_2, dx_3, dx_4) . Einstein's fundamental hypothesis is this: there exists a set of quantities g_{rs} such that

$$g_{11}dx_1^2 + 2g_{12}dx_1dx_2 + \dots + g_{44}dx_4^2$$

has the same value, no matter how the four-dimensional map is strained. In any strain g_{rs} is, of course, changed, as are also the differences dx .* [中文](#)

If the above expression be denoted by $(ds)^2$, ds may conveniently be called the *interval* between two events (not, of course, in the sense of time interval). In the case of a field in which there is no gravitation at all, if dx_4 is taken to be dt , it is supposed that ds^2 reduces to the expression $dx_1^2 + dx_2^2 + dx_3^2 - c^2dt^2$, where c is the velocity of light. If this is put equal to zero, it simply expresses the condition that

the neighbouring events correspond to two events in the history of a point travelling with the velocity of light. [中文](#)

Einstein is now able to write down differential equations connecting the quantities g_{rs} with the coordinates (x_1, x_2, x_3, x_4) , which are in complete accord with the requirement of complete relativity.[†] These equations are assumed to hold at all points of space unoccupied by matter, and they constitute Einstein's law of gravitation. [中文](#)

Planetary Motion

The next step is to find a solution of the equations when there is just one point in space at which matter is supposed to exist, one point which is a singularity of the solution. This can be effected completely[‡]: that is, a unique expression is obtained for the interval between two neighbouring events in the gravitational field of a single mass. This mass is now taken to be the sun. [中文](#)

It is next assumed that in the four-dimensional map (which, by the way, has now a bad twist in it, that cannot be strained out, all along the line of points corresponding to the positions of the sun at every instant of time) the path of a particle moving under the gravitation of the sun will be the most direct line between any two points on it, in the sense that the sum of all the intervals corresponding to all the elements of its path is the least possible.[§] Thus the equations of motion are written down. The result is this:

The motion of a particle differs only from that given by the Newtonian theory by the presence of an additional acceleration towards the sun equal to three times the mass of the sun (in gravitational units) multiplied by the square of the angular velocity of the planet about the sun. [中文](#)

In the case of the planet Mercury, this new acceleration is of the order of 10^{-8} times the Newtonian acceleration. Thus up to this order of accuracy Einstein's theory actually arrives at Newton's laws: surely no

dethronement of Newton.

中文

The effect of the additional acceleration can easily be expressed as a perturbation of the Newtonian elliptic orbit of the planet. It leads to the result that the major axis of the orbit must rotate in the plane of the orbit at the rate of 42.9" per century.

中文

Now it has long been known that the perihelion of Mercury does actually rotate at the rate of about 40" per century, and Newtonian theory has never succeeded in explaining this, except by *ad hoc* assumptions of disturbing matter not otherwise known.

中文

Thus Einstein's theory almost exactly accounts for the one outstanding failure of Newton's scheme, and, we may note, does not introduce any discrepancy where hitherto there was agreement.

中文

The Deflection of Light by Gravitation

The new theory having justified itself so far, it was thought worth while for British astronomers to devote their main energies at the recent solar eclipse to testing its prediction of an entirely new phenomenon.

中文

As was remarked above, the propagation of light in the ordinary case of freedom from gravitational effect is represented by the equation $ds = 0$.

中文

This Einstein boldly transfer to his generalised theory. After all, it is quite a natural assumption. The propagation of light is a purely objective phenomenon. The emission of a disturbance from one point at one moment, and its arrival at another point at another moment, are events distinct and independent of the existence of an observer. Any law that connects them must be one which is independent of the map the observer uses; ds being an invariant quantity, $ds = 0$ expresses such an invariant law.

中文

This leads at once to a law of variation of the velocity of light in the gravitational field of the sun.

$$v = c(1 - 2m/r)$$

Here m , as before, is the mass of the sun in gravitational units, and is equal to 1.47 kilometres, while c is the velocity of light at a great distance from the sun. Thus the path of a ray is the same as that if, on the ordinary view, it were travelling in a medium the refractive index of which was $(1 - 2m/r)^{-1}$. In this medium the refractive index would increase in approaching the sun, so that the rays would be bent round towards the sun in passing through it. The total amount of the deflection for a ray which just grazes the sun's surface works out to be 1.75", falling off as the inverse of the distance of nearest approach.

中文

The apparent position of a star near to the sun is thus further from the sun's centre than the true position. On the photographic plate in the actual observations made by the Eclipse Expedition the displacement of the star image is of the order of a thousandth of an inch. The measurements show without doubt such a displacement. The stars observed were, of course, not exactly at the edge of the sun's disc; but on reduction, allowing for the variation inversely as the distance, they give for the bend of a ray just grazing the sun the value 1.98", with a probable error of 6 percent, in the case of the Sobral expedition, and of 1.64" in the Principe expedition. 中文

The agreement with the theory is close enough, but, of course, alternative possible causes of the shift have to be considered. Naturally, the suggestion of an actual refracting atmosphere surrounding the sun has been made. The existence of this, however, seems to be negated by the fact that an atmosphere sufficiently dense to produce the refraction in question would extinguish the light altogether, as the rays would have to travel a million miles or so

through it. The second suggestion, made by Prof. Anderson in *Nature* of December 4, that the observed displacement might be due to a refraction of the ray in travelling through the earth's atmosphere in consequence of a temperature gradient within the shadow cone of the moon, seems also to be negatived. Prof. Eddington estimates that it would require a change of temperature of about 20 °C per minute at the observing station to produce the observed effect. Certainly no such temperature change as this has ever been noted; and, in fact, in Principe, at which the Cambridge expedition made its observations, there was practically no fall of temperature. 中文

Gravitation and the Solar Spectrum

It was suggested by Einstein that a further consequence of his theory would be an apparent discrepancy of period between the vibrations of an atom in the intense gravitational field of the sun and the vibrations of a similar atom in the much weaker field of the earth. This is arrived at thus. An observer would not be able to infer the intensity of the gravitational field in which he was placed from any observations of atomic vibrations in the same field: that is, an observer on the sun would estimate the period of vibration of an atom there to be the same that he would find for a similar atom in the earth's field if he transported himself thither. But on transferring himself he automatically changes his scale of time; in the new scale of time the solar atom vibrates differently, and, therefore, is not synchronous with the terrestrial atom. 中文

Observations of the solar spectrum so far are adverse to the existence of such an effect. What, then, is to be said? Is the theory wrong at this point? If so, it must be given up, in spite of its extraordinary success in respect of the other two phenomena. 中文

Sir Joseph Larmor, however, is of opinion that Einstein's theory itself does not in reality predict the displacement at all. The present writer

shares his opinion. Imagine, in fact, two identical atoms originally at a great distance from both sun and earth. They have the same period. Let an observer A accompany one of these into the gravitational field of the sun, and an observer B accompany the other into the field of the earth. In consequence of A and B having moved into different gravitational fields, they make different changes in their scales of time, so that actually the solar observer A will find a different period for the solar atom from that which B, on the earth, attributes to his atom. It is only when the two observers choose so to measure space and time that they consider themselves to be in identical gravitational fields that they will estimate the periods of the atoms alike. This is exactly what would happen if B transferred himself to the same position as A. Thus, though an important point remains to be cleared up, it cannot be said that it is one which at present weighs against Einstein's theory. 中文

(104, 394-395; 1919)

* The gravitational field is specified by the set of quantities g_{rs} . When the gravitational field is small, these are all zero, except for g_{44} , which is approximately the ordinary Newtonian gravitational potential.

† These equations take the place of the old Laplace equation $\nabla^2 V = 0$. Just as that equation is the only differential equation of the second order which is entirely independent of any change of ordinary space coordinates, so Einstein equations are uniquely determined by the condition of relativity.

‡ The result is that the invariant interval ds is given by $ds^2 = (1 - 2m/r)(dt^2 - dr^2) - r^2(d\theta^2 + \sin^2\theta d\phi^2)$, the four coordinates being now interpreted as time and ordinary spherical polar coordinates.

§ This corresponds to the fact that in a field where there is no acceleration at all the path of a particle is the shortest distance between two points.

爱因斯坦关于万有引力的相对论

坎宁安

阿瑟·爱丁顿最近宣布，他在日食期间对星光偏转的测量明确地证实了爱因斯坦的广义相对论。在这篇文章中，埃比尼泽·坎宁安简单描述了爱因斯坦的理论。爱因斯坦在1905年就已经建立了惯性和能量之间的联系，他现在的工作主要是考查重力是否也有可能与能量相关联。坎宁安指出，这个理论说明了这样一个观点：虽然不存在衡量空间间隔和时间间隔完全相等的绝对标准，但可以设计无限多种方式以保证多个物理事件的等同性。他说，爱因斯坦利用黎曼、列维齐维塔和其他人的数学理论已经验证了这些结论。 [英文](#)

I

在11月6日皇家学会和皇家天文学会共同举办的会议上宣布的日食观测结果，使得爱因斯坦关于万有引力的新理论受到了公众的广泛关注。这个理论在战争之前就已经被提出来了；它是在战争中极少数没有被丢到一边的纯科学工作之一；日食观测的准备工作在战争结束之前就已经着手进行了。 [英文](#)

如果在试图理解这个新理论之前，我们就已经像日报上说的那样，认为牛顿在其面前也会黯然失色，那么最好首先回顾一下牛顿所做的工作。并不能说牛顿是第一个使用微分计算的人。有些议论认为这是莱布尼茨的首创。牛顿也不是第一个认识到惯性和力之间关系的人。这方面，肯定是伽利略首先对此进行了初步的设想。开普勒在很久以前就对万有引力有过模糊的猜想，但是，引力与距离平方成反比的规律是在该“原理”建立之前，由胡克首先发现的。牛顿所做工作的杰出之处在于，他把这么多松散的线索整合到了一起。行星运动（已被开普勒精确

描述过)、日常生活中的落体运动、潮汐的涨落、地轴的进动以及在月球和行星运动中出现的许多小的不规则性——牛顿将所有这些现象都统一了起来。牛顿把所有这些都归入了一个包括力学三大定律和简洁的平方反比关系的基本框架中，也难怪在后来很长一段时间内，科学上的思索都停滞了。整个宇宙都看似简单而圆满。在后来至少一个世纪的时间里，除了在形式上发展一下牛顿力学，没有其他工作可做。在18世纪中叶，莫佩尔蒂暗示了一种新的物理学说。他不满足于认为宇宙是一个在某种确定的法则下永不停止、永不倒退的钟表。宇宙的运动一定是有目的的，一定有一种神圣的力量在支配着它的运动。因此，他提出了最小作用原理。但是人们很快发现这只不过是牛顿定律的一种新的外在形式而已，然后18世纪就这样结束了。 英文

19世纪发生了重大的变化。在这个世纪末，电的时代到来了。人类要揭示原子中的秘密。太空也不再是有行星在其中运行的寒冷而空洞的广袤真空。宇宙中的每个部分都注满了运动着的能量。以太，而不是物质，才是最终的存在形式。物质实际上都是带电的。一个重大的问题摆在了当代人的面前：如何将新的电学理论和经典的牛顿力学原理统一起来。这样，最小作用原理就变得重要起来；因为它是新旧两种宇宙观相通的部分，在两者中，动能和势能之差的时间平均都应该取最小值。

英文

物质的电学理论遇到的一个最主要的问题是，无法把万有引力引入到这个理论框架之中。在电学理论遵从平方反比定律的情况下，新兴的原子物理的蓬勃发展却被忽视掉了，电学独自向破解宇宙之谜的目标发起了挑战。电学理论力图说明物质的所有其他性质，而唯独将人们最为熟知的属性排除在外。它可以说青铜和玻璃之间存在差别的原因，但是不能解释它们共同的特性：重量。至此，以太学说也开始默默地销声匿迹了。 英文

在牛顿的宇宙框架中最令人困扰的一点是：它无法与时空相对性的哲学学说达成一致。加速度在力学中是一个关键的量，它反映了物体运动状态的变化。但这并不意味着牛顿假设了空间中存在一个终极的参考系，一个物体的实际速度相对于这个参考系是唯一确定的，因为在他的理论中，任意一个质点的运动速度总可以加上一个常数速度。这种处理

方法的严重缺陷是，当处理两个参考系的问题时，如果其中一个参考系相对于另一个做转动或者非匀速运动，那么前面所说的法则就不可能保持如此简单的形式。这样看来，如果牛顿是正确的，那么在空间中，“固定方向”是有意义的，但“固定位置”却没有任何意义。两者看似应该同时成立或者同时不成立，但是物理上的关系显然是有区别的。为什么会这样呢？我们还不知道。无论我们采用什么样的新理论，都要考虑到上面的问题。 [英文](#)

当我们引入了以太的概念，用它来代替空无一物的空间时，问题看似得到了解决，尽管我们也许注意到，在传播这一概念的时候，一些哲学家，比如孔德，认为无限且无形的以太和绝对空间一样不合逻辑。但让我们先把这些看法抛在一边，物理学家们提出要测量所有相对于以太的平动和转动。唉！可惜以太却拒绝我们的测量。很快就出现了对这一难题的解释，但是这与能够用一种大家可以接受的方式来为以太辩解还有非常遥远的距离。无论如何，它们证明了这种科学想象的创造并不是唯一的，而是有很多种。我们渴望找到一种可以用来测量运动的永久标准，而以太的概念是非常失败的。问题和从前一样没有得到解决。还是战争之前由爱因斯坦于1905年总结出来的相对论解决了这个问题。物理学家们则强烈地抱怨爱因斯坦摒弃了他们的以太。 [英文](#)

但是，我们不要以为后来提出的假说都是不正确的。这些假说明确地表明现有的许多观点需要修正，并且说明了修正的方向应该在哪里。尤其是它强调了一个事实：惯性不是物质的一个不会发生变化的基本属性，而应该被看作是随着能量的变化而变化的。我们要再次强调，能量是一个相对量。一个绝对量是独立不变的；它不依赖于观察者的体验和想象，这就是“作用”。当以太及与它相关的测量系统被选择作为大量作用中的任意一员时，它们都满足最小作用原理，并且作用量的总和不变。 [英文](#)

但是，万有引力仍然没有被考虑进去，爱因斯坦正是从这个问题出发，现已成功地获得了巨大的进展。如果能量和惯性是不可分割的，那么重力难道就不能建立在能量的基础之上吗？如果能量是一束具有动量的光束，那么它为什么不能有重量呢？ [英文](#)

这样的想法是革命性的，尽管它还不够成熟。因为，如果这是可能的，那么它就意味着需要重新考虑光速不变性和普适性的假说。这个假说是尚不成熟的相对论的基本原则。但是如果它被质疑，如果光速只是因为通常的测量方法不够精确才大致不变，那么，被大家普遍接受的相对论法则就只是一种近似，就像它本身的系统一样。但这是对什么的近似呢？只能是对一种更加普遍的原理的近似。当消除了那种根本上的限制以后，原来的法则中还有没有什么东西可以保留下来呢？ 英文

就是在这个问题上，哲学家们批判了爱因斯坦早期的工作。对物理学家来说，这样的批评太偏激了。对哲学家来说，这种批评还远算不上严厉。爱因斯坦开始寻找一种彻底的时空相对论。他认为，除了完全重合之外，不存在衡量空间间隔和时间间隔完全相等的绝对标准。他只要要求观察者观察到的事件的发生顺序和物体摆放的顺序不被打乱。在这个前提下，任何测量方法都将是可行的。这就好像我们可以用墨卡托投影法、心射切面投影法、立体投影法或者任何一种其他的方法去画地球，而没有人会说其中哪一种地图较之其他地图更准确。飞行员和海员使用任何一种地图都是安全可靠的。因此，也有很多方法可以标定时空中事件发生的顺序，每一种都描述了真实的情况，每一种都同样可信。

英文

这样，爱因斯坦接下来就只需要解决那些数学上的问题了。他所需要的纯数学方法已经存在。绝对微分、微分不变量理论，这些都是已知的。大多数人经常研读的纯数学著作，如黎曼、克里斯托弗尔、里奇和列维齐维塔的著作，都为爱因斯坦提供了必要的数学工具。剩下的工作就是从那些方程和表达式中选出最接近数学物理的部分，并想办法把它们解出来。 英文

II. 理论的本质

第一篇文章旨在说明爱因斯坦的思考方法，从物理学的角度来看，简要的说明就是这样。牛顿明确地将万有引力和质量联系起来。电磁学理论表明，一个物体的质量并不是物质确定不变的内在属性。光能和热能当然都具有惯性，那么，它也会受到万有引力的影响吗？如果确实如

此，确切的作用方式又是怎样的呢？厄缶的精确实验更表明了由其惯性所表示的物体质量同样受到万有引力的影响。 [英文](#)

牛顿万有引力定律的描述要怎样修正才能符合关于质量的新观点呢？电磁学理论和战争前提出的相对论要怎样调整才能允许万有引力效应的存在呢？在解除了光速不变的约束之后，相对论原理会不会成为一种更加普遍且被相对性的哲学理论所接受的法则呢？或者说，另一方面，它会不会被证明完全不可行呢？ [英文](#)

这里马上就引出了一个观点。彻底的相对论者只能对速度进行绝对测量，却不能对加速度进行绝对测量。然而，加速运动在万有引力场中会发生明显的变化；因此在任意地点，万有引力的测量值肯定都是相对的，它取决于测量者所选择的测量速度和加速度的方式。这是爱因斯坦的主要观点之一。在力学上，对所谓“离心力”和“万有引力”的解释通常是有区别的。前者是一个虚拟的力，仅仅表现了物体要做匀速直线运动的趋势。另一方面，万有引力被认为是一个真实的力，因为它和作用于物体的外界因素有关。 [英文](#)

爱因斯坦让我们考虑，如果这种区别不是本质的，结果会怎样。这就是他所说的“等效原理”。它立刻就引出了这样的设想：一束光穿过万有引力场时会发生弯曲。一个在地球表面附近的观察者会看到物体远离自己落向地球。一般来说，他会把这归结为地球的引力。如果他和物体一起下落，那么他对万有引力的感觉就会消失。他的怀表不再压在衣袋底部，他的脚也不再压在靴子上。对于这位正在下落的观察者来说，他是观察不到万有引力存在的。如果他有时间观察和思考光的传播，那么按照等效原理，他将看不到光线的直线运动被万有引力所干扰。换句话说，一束沿水平方向传播的光线，将与观察者一起同时做垂直运动。因此，一个没有下落的观察者可以感觉到万有引力的存在，所以光线在向地球运动的过程中会发生弯曲。 [英文](#)

就像前面提到的那样，要把这样一个想法系统地求解出来，需要大量的数学运算。这里我们所能做的只是用模糊的示意来说明这个原理，主要通过类比法。 [英文](#)

把时间作为第四维并不是一个新的发现。每一个人在某种程度上都

会把世界历史的一段时期当作一个整体来看待。在这样做的时候，时间段和空间段没有什么区别。在匆匆一瞥之中所有的东西都呈现到他面前要他去了解。他在仔细考虑一系列事件发生时间的同时，还要将它们和发生地点联系起来。比如，他能同时从时间顺序和疆域范围两方面来考虑大英帝国的扩张。所以可以这样说，他可以画一个地图，一个四维的地图，尽管不能画在纸上，但依然可以描述一系列事件。 [英文](#)

让我们用我们所熟悉的二维地图进行类比。我们可以想象有一个描述世界上某个区域的地图，用来制作这个地图的材料可以不受物理限制，随意延展和扭曲以保持它的连续性。不管这种材料如何扭曲变形，它上面表示地点次序的连续直线依然保持连续，沿着这条直线各个地点的排列顺序不变。这种地图无法记录旅行的距离，但是它可以忠实地记录某些特定的事实，比如，伦敦位于英国境内，从伦敦到另一个地方——巴黎，不可能不跨越海洋。但是一般地图所具有的记录任意一小块地方的功能在这种地图中完全丧失了。 [英文](#)

在地球表面从一地到另一地的最短路径是沿着大圆的路径；在普通的地图上，一系列的大圆，即经线，是用一系列的直线来表示的。初看起来，我们的可伸缩地图可以被拉伸开，这样，地球表面的所有大圆都可以呈直线。可事实并不是这样。我们可以把经线和另外一组由地球的另外一个直径确定的大圆表示成两组直线，但是这样做之后，所有其他的大圆就只能表示为曲线了。 [英文](#)

将上述观点扩展到四维时空，就构成了爱因斯坦的基本概念。我们通常认为在没有万有引力的世界里，自由粒子将永远静止或者做匀速直线运动。我们可以想象一下，在四维的地图中，粒子的历史被记录为一条直线。如果这个粒子是静止的，那么这条直线就平行于时间轴，否则就是倾斜的。现在，如果地图以任意方式被拉伸，那么粒子的路径就不再被表示为直线。如果我们能接受可伸缩地图作为表征事实的方式，就可以把这些弯曲的路径看作是“万有引力场”的证据，但是，这种引力场也可以马上被解释成是由这种特殊的表示方法造成的，因为所有路径都可以变成直线。 [英文](#)

但是类似的二维地图告诉我们，没有任何一种变形方式可以使所有

记录自由粒子历史的线都同时呈直线；关于这一点，纯数学可以给出它在几何学上的精确证明，还可以给出表达式，用来度量那些不可消除的弯曲。天才的黎曼和克里斯托弗尔给出了我们所需的微积分算法。

[英文](#)

现在，爱因斯坦认为，无法消除的弯曲表示物质的存在。这意味着，如果某个数学表达式为零则表示没有物质存在。于是他写出了自由空间中万有引力场的定律。另一方面，如果表达式不为零，那么它们一定等于描述物质及其运动的物理量。这些方程就是爱因斯坦在有物质存在的点上构筑的万有引力定律表达式。

[英文](#)

读者可能会问：这些方程中都有哪些物理量？在这里我们只能给出一个非常不充分的回答。如果在四维地图中，两个相邻的点被认为代表两个相邻的事件，那么用普通几何方法测量的两点之间的实际距离将没有任何物理意义。如果这个地图发生变形，它就会被改变，所以对于相对论者来说，撇开观察者反复无常的测量结果，它代表了某种不存在于由事件组成的外部世界中的东西。但是爱因斯坦认为有一个物理量依赖于两个点之间的关系，具有不变性，也就是说，它不依赖于某种事件地图。比较一个地图和另一个地图，设想其中一个发生变形而成为另一个，代表两个事件的点的相对位置会随着变形方式的变化而变化。可以假设，任意点的变形可以用一些物理量来表示（一般记做 g_{rs} ），而不变量是这些物理量和事件点相对位置的函数。

[英文](#)

这个表征万有引力场的物理量 g_{rs} 被引入构成万有引力新定律的微分方程中。

[英文](#)

当然，我们不可能用非数学语言将这个理论用数字精确地表达出来。但是这篇文章的主要目的是说明它的普遍特征。这个理论与许多其他理论的不同之处在于，它不是为了解释某个新发现而被构建的。构建它的目的是为了满足精神上的渴望和应对哲学上的质疑。它在本质上是纯数学问题。这个问题给我们的第一印象是，它是不可能被攻破的；第二点出人意料的是，它居然被攻破了；第三个令人惊奇的是，它竟然预言了可以用实验研究的现象。关于最后一方面以及对其预言的证实将是下一篇文章的主题。

[英文](#)

III . 关键的现象

上周的文章旨在说明一个完全的相对论者对万有引力物质必须遵循的法则的态度。而本文是要介绍一些特定的结论。[英文](#)

闵可夫斯基这样评论爱因斯坦早期的狭义相对论：“从今以后，单独的空间和单独的时间都将不存在；二者只能作为一个复合体而存在”（《空间和时间》，1908年）。在这个描述了所有历史事件的四维空间中， (x_1, x_2, x_3, x_4) 被视为一组坐标。把任意一组特定数值代入坐标中，都能表示一个事件。如果一个观察者观察到发生地点和时间都很接近的两个事件，那么四维地图上相应两点的坐标也区别不大。我们把它们之间的差别表示为 (dx_1, dx_2, dx_3, dx_4) 。爱因斯坦的基本假设是这样的：存在一组 g_{rs} ，无论四维地图发生什么样的变形，

$$g_{11}dx_1^2 + 2g_{12}dx_1dx_2 + \dots + g_{44}dx_4^2$$

都具有相同的值。在发生变形时， g_{rs} 的值当然会发生变化，差值 dx 同样会改变。^{*} [英文](#)

如果上面的表达式被记作 $(ds)^2$ ，为方便起见，我们可以把 ds 称作两个事件的间隔（当然不是一般观念中的时间间隔）。在万有引力场不存在的情况下，如果 dx_4 用 dt 来代替，那么 ds^2 就会退化成表达式 $dx_1^2 + dx_2^2 + dx_3^2 - c^2dt^2$ ，这里 c 是光速。如果这个表达式等于零，则表示一个以光速运动的点所经历的两个相邻的事件。[英文](#)

现在，爱因斯坦就可以写出将物理量 g_{rs} 与坐标 (x_1, x_2, x_3, x_4) 相联系的微分方程了，这与完善相对论的要求完全一致。[†] 这些方程包含了空间中所有未被物质占据的点，它们构成了爱因斯坦的万有引力定律。

[英文](#)

行星的运动

下一步的任务是找到一个空间中只有一个点被物质占据的方程解，而这个点是解的奇点。这完全可以做到[‡]：也就是说，对于单一质点在引力场中的两个相邻事件的间隔，我们可以得到唯一的表达式。太阳可以

当作这样的一个质点。 [英文](#)

接下来假设在四维地图（现在这个地图严重扭曲，不能把对应于太阳每个时刻位置的点组成的线拉伸开）中，在太阳引力场中运动的质点的路径将是图上任意两点之间最直的线，即与路径上所有组成部分对应的所有间隔之和尽可能最小。[§]这样，就可以写出运动方程。结果如下：

一个质点的运动与牛顿理论给出的运动的不同之处在于多出了一个朝向太阳的加速度，这个加速度的值等于三倍的太阳质量（万有引力单位）乘以行星绕太阳运动的角速度的平方。 [英文](#)

对于水星，这个新加速度的量级是牛顿加速度的 10^{-8} 。这样，低于这个精确度，爱因斯坦理论就还原成了牛顿理论：牛顿理论当然不会失效。 [英文](#)

这个多出来的加速度可以被看作是牛顿椭圆行星轨道的一种扰动。这就造成了轨道主轴在轨道平面中以每世纪42.9角秒的速度进动。

[英文](#)

很久以前我们就知道，水星的近日点的确在以每世纪约40角秒的速度进动，牛顿理论从来没有成功地解释过这个现象，除非特意假设有一个在其他情况下未曾出现的干扰物体。 [英文](#)

这样，爱因斯坦的理论就彻底解决了牛顿理论框架中的一个重要不足，并且，我们注意到，爱因斯坦理论和牛顿理论没有矛盾，至今它们仍然是统一的。 [英文](#)

光在万有引力作用下的偏转

到目前为止，这个新理论的正确性已经得到了证明，英国天文学家们正将他们的主要精力放在近期的日食上，为的是检验此理论所预言的一个全新的现象，大家都认为这是一件值得做的事情。 [英文](#)

正如上面所说的那样，在没有万有引力效应的情况下，光的传播可以表示为方程 $ds = 0$ 。 [英文](#)

爱因斯坦大胆地将它移植到了他的广义理论中。毕竟，这是一个很自然的假设。光的传播是一个纯客观的现象。在某一时刻某一点发生的干扰，以及这个干扰在另一时刻到达另一点，这两者是不同的事件，与观察者是否存在无关。任何将它们联系起来的法则都一定不依赖于观察者所使用的地图； ds 是一个不变的量， $ds = 0$ 表示出了这样一个不变的法则。 [英文](#)

这立刻就引出了在太阳引力场中光速不变的定律。

$$v = c(1 - 2m/r)$$

这里的 m 和前面一样，是太阳在万有引力单位下的质量，它相当于1.47千米， c 是远离太阳处的光速。这样，从通常的观点上看，一束光的行进路线和它在折射率为 $(1 - 2m/r)^{-1}$ 的介质中传播一样。在这个介质中，越接近太阳折射率就越大，所以光线在经过太阳的时候就会发生弯曲。一束刚好掠过太阳表面的光的偏转角度是1.75角秒，偏转角度会随着光线与太阳之间最小距离的倒数的减小而减小。 [英文](#)

靠近太阳的恒星的视位置比它的真实位置离日心更远。在观测日食时所拍的照相底片上，恒星图像位移的数量级为千分之一英尺。测量结果毫无疑问地显示了这样的一个位移。当然，观测的恒星并非恰好在日面的边缘；但是可以利用偏转量和距离成反比的关系进行化规，在索布拉尔的观测队测算出一束刚好掠过太阳表面的光线的偏转角度是1.98角秒，允许的误差范围是6%；在普林西比岛的观测队得到的结果是1.64角秒。 [英文](#)

实验和理论已经足够吻合，但是，也必须考虑到引起位移的其他可能原因。很自然的，有人怀疑在太阳周围有一个能发生真正的折射效应的大气层。但是，它的存在却可以被以下因素否定，即产生这样的折射作用要求大气层足够厚，而这么厚的大气层会使光线消失，因为光线需要经过100万公里左右才能穿过去。第二种可能性是安德森教授在12月4日的《自然》上提出的。他认为，观察到的位移可能是由光线穿过地球大气层时的折射造成的，因为在月影锥内存在温度梯度，温度梯度可以引发折射现象，这个猜测也不成立。爱丁顿教授估算过，要产生我们观测到的效应，观测站的温度变化应达到每分钟20℃之多。这样的温度变

化当然从未有过；事实上，在剑桥考察队进行观测的普林西比岛，温度并未下降过。 [英文](#)

万有引力和太阳光谱

爱因斯坦指出，他的理论还会进一步导出这样的结果：原子在太阳的强引力场中的振动周期和其在弱得多的地球引力场中的振动周期有明显的差别。这个结果是这样得到的：当一个观察者与他所观察的振动原子处在同一个引力场中时，他不可能通过观察原子的振动来判断这个引力场的强度。也就是说，一个在太阳上的观察者测量到的原子振动周期与一个相似原子在地球上的振动周期相同，前提是他本人来到地球。但是在他转换观测地点的时候，他会自动调整时间尺度；在新的时间尺度中，太阳引力场中的原子振动周期将发生变化，所以就与地球上的原子不同步了。 [英文](#)

迄今为止，太阳光谱的观测结果并不支持这种效应的存在。接下来我们该说些什么呢？这个理论在这一点上是否错了？如果是这样，它必须被放弃，尽管它成功地解释了另外两个现象。 [英文](#)

然而，约瑟夫·拉莫尔爵士认为，事实上爱因斯坦的理论本身并没有预言过这种移位效应。本文作者也同意他的观点。事实上，我们可以想象，两个相同的原子最初处于既远离太阳又远离地球的某地。它们具有相同的周期。让观察者A伴随着其中一个原子来到太阳引力场中，让观察者B伴随着另一个原子来到地球引力场中。由于A和B进入的引力场不同，他们的时间尺度发生的变化也不同，因此，太阳上的观察者A将发现太阳上原子的振动周期与地球上的观察者B看到的地球上原子的振动周期不同。只有当两个观察者在同一个引力场中来测量时空时，他们才会判断出两原子的周期相同。如果B来到A的位置，就会发生以上所说的情况。所以，尽管还有一个要点有待澄清，但我们目前还不能说这是一个与爱因斯坦理论相悖的现象。 [英文](#)

（王静 翻译；鲍重光 审稿）

* 万有引力场由一组物理量 g_{rs} 来说明，当万有引力场很小的时候，

这些值除了 g_{44} 以外都为零，这就近似成为牛顿的万有引力势场。

† 这些方程代替了旧的拉普拉斯方程 $\nabla^2 V = 0$ 。正如拉普拉斯方程是唯一一个完全不受普通空间坐标体系变化影响的二阶微分方程一样，爱因斯坦方程是唯一一个由相对论条件确定的方程。

‡ 结果是：不变的间隔 ds 可以由下式确定， $dx^2 = (1 - 2m/r)(dt^2 - dr^2) - r^2(d\theta^2 + \sin^2\theta d\phi^2)$ ，这四个坐标可以解释为时间和普通的球面极坐标。

§ 它对应于这样一个事实：在一个没有加速度的场中，粒子运动的路径是两点之间的最短距离。

A Brief Outline of the Development of the Theory of Relativity*

A. Einstein

By 1921, Einstein's theory of relativity was widely accepted. Here he describes the theory's historical development, starting from the aim to rid physics of reliance on action at a distance. Maxwell had achieved this for electricity and magnetism, and his mathematical formulation led others to suppose that all space is filled with an ether that carried the electric and magnetic fields. This led to difficulties, which Einstein overcame by abandoning the belief that events may be simultaneous regardless of an observer's motion. But this new understanding didn't encompass gravity. The supposition that gravity and inertia are identical prompted the general theory of relativity. Einstein wonders if gravitational and electrical phenomena might be unified in a theory of all nature's forces—a theory physicists still seek today. [中文](#)

THERE is something attractive in presenting the evolution of a sequence of ideas in as brief a form as possible, and yet with a completeness sufficient to preserve throughout the continuity of development. We shall endeavour to do this for the Theory of Relativity, and to show that the whole ascent is composed of small,

almost self-evident steps of thought.

[中文](#)

The entire development starts off from, and is dominated by, the idea of Faraday and Maxwell, according to which all physical processes involve a continuity of action (as opposed to action at a distance), or, in the language of mathematics, they are expressed by partial differential equations. Maxwell succeeded in doing this for electro-magnetic processes in bodies at rest by means of the conception of the magnetic effect of the vacuum-displacement-current, together with the postulate of the identity of the nature of electro-dynamic fields produced by induction, and the electro-static field.

[中文](#)

The extension of electro-dynamics to the case of moving bodies fell to the lot of Maxwell's successors. H. Hertz attempted to solve the problem by ascribing to empty space (the ether) quite similar physical properties to those possessed by ponderable matter; in particular, like ponderable matter, the ether ought to have at every point a definite velocity. As in bodies at rest, electro-magnetic or magneto-electric induction ought to be determined by the rate of change of the electric or magnetic flow respectively, provided that these velocities of alteration are referred to surface elements moving with the body. But the theory of Hertz was opposed to the fundamental experiment of Fizeau on the propagation of light in flowing liquids. The most obvious extension of Maxwell's theory to the case of moving bodies was incompatible with the results of experiment.

[中文](#)

At this point, H. A. Lorentz came to the rescue. In view of his unqualified adherence to the atomic theory of matter, Lorentz felt unable to regard the latter as the seat of continuous electro-magnetic fields. He thus conceived of these fields as being conditions of the ether, which was regarded as continuous. Lorentz considered the ether to be intrinsically independent of matter, both from a mechanical and a physical point of view. The ether did not take part in the motions of matter, and a reciprocity between ether and matter could be assumed

only in so far as the latter was considered to be the carrier of attached electrical charges. The great value of the theory of Lorentz lay in the fact that the entire electro-dynamics of bodies at rest and of bodies in motion was led back to Maxwell's equations of empty space. Not only did this theory surpass that of Hertz from the point of view of method, but with its aid H. A. Lorentz was also pre-eminently successful in explaining the experimental facts. 中文

The theory appeared to be unsatisfactory only in *one* point of fundamental importance. It appeared to give preference to one system of coordinates of a particular state of motion (at rest relative to the ether) as against all other systems of coordinates in motion with respect to this one. In this point the theory seemed to stand in direct opposition to classical mechanics, in which all inertial systems which are in uniform motion with respect to each other are equally justifiable as systems of coordinates (Special Principle of Relativity). In this connection, all experience also in the realm of electro-dynamics (in particular Michelson's experiment) supported the idea of the equivalence of all inertial systems, *i.e.* was in favour of the special principle of relativity. 中文

The Special Theory of Relativity owes its origin to this difficulty, which, because of its fundamental nature, was felt to be intolerable. This theory originated as the answer to the question: Is the special principle of relativity really contradictory to the field equations of Maxwell for empty space? The answer to this question appeared to be in the affirmative. For if those equations are valid with reference to a system of coordinates K , and we introduce a new system of coordinates K' in conformity with the—to all appearances readily establishable—equations of transformation

$$\left. \begin{aligned} x' &= x - vt \\ y' &= y \\ z' &= z \\ t' &= t \end{aligned} \right\} \text{(Galileo transformation),}$$

then Maxwell's field equations are no longer valid in the new coordinates (x', y', z', t') . But appearances are deceptive. A more searching analysis of the physical significance of space and time rendered it evident that the Galileo transformation is founded on arbitrary assumptions, and in particular on the assumption that the statement of simultaneity has a meaning which is independent of the state of motion of the system of coordinates used. It was shown that the field equations for *vacuo* satisfy the special principle of relativity, provided we make use of the equations of transformation stated below:

$$\left. \begin{aligned} x' &= \frac{x - vt}{\sqrt{1 - v^2/c^2}} \\ y' &= y \\ z' &= z \\ t' &= \frac{t - vx/c^2}{\sqrt{1 - v^2/c^2}} \end{aligned} \right\} \text{(Lorentz transformation)}$$

In these equations x, y, z represent the coordinates measured with measuring-rods which are at rest with reference to the system of coordinates, and t represents the time measured with suitably adjusted clocks of identical construction, which are in a state of rest. 中文

Now in order that the special principle of relativity may hold, it is necessary that all the equations of physics do not alter their form in the transition from one inertial system to another, when we make use of the Lorentz transformation for the calculation of this change. In the language of mathematics, all systems of equations that express physical laws must be co-variant with respect to the Lorentz transformation. Thus, from the point of view of method, the special principle of relativity is comparable to Carnot's principle of the impossibility of perpetual motion of the second kind, for, like the latter, it supplies us with a general condition which all natural laws must satisfy. 中文

Later, H. Minkowski found a particularly elegant and suggestive

expression for this condition of co-variance, one which reveals a formal relationship between Euclidean geometry of three dimensions and the space-time continuum of physics. 中文

<i>Euclidean Geometry of Three Dimensions.</i>	<i>Special Theory of Relativity.</i>
Corresponding to two neighbouring points in space, there exists a numerical measure (distance ds) which conforms to the equation $ds^2 = dx_1^2 + dx_2^2 + dx_3^2$	Corresponding to two neighbouring points in space-time (point events), there exists a numerical measure (distance ds) which conforms to the equation $ds^2 = dx_1^2 + dx_2^2 + dx_3^2 + dx_4^2$
It is independent of the system of coordinates chosen, and can be measured with the unit measuring-rod.	It is independent of the inertial system chosen, and can be measured with the unit measuring-rod and a standard clock. x_1, x_2, x_3 are here rectangular coordinates, whilst $x_4 = \sqrt{-1}ct$ is the time multiplied by the imaginary unit and by the velocity of light.
The permissible transformations are of such a character that the expression for ds^2 is invariant, i.e. the linear orthogonal transformations are permissible.	The permissible transformations are of such a character that the expression for ds^2 is invariant, i.e. those linear orthogonal substitutions are permissible which maintain the semblance of reality of x_1, x_2, x_3, x_4 . These substitutions are the Lorentz transformations.
With respect to these transformations, the laws of Euclidean geometry are invariant.	With respect to these transformations, the laws of physics are invariant.

中文

From this it follows that, in respect of its *rôle* in the equations of physics, though not with regard to its physical significance, time is equivalent to the space coordinates (apart from the relations of reality). From this point of view, physics is, as it were, a Euclidean geometry of four dimensions, or, more correctly, a statics in a four-dimensional Euclidean continuum. 中文

The development of the special theory of relativity consists of two main steps, namely, the adaptation of the space-time “metrics” to Maxwell’s electro-dynamics, and an adaptation of the rest of physics to that altered space-time “metrics”. The first of these processes yields the relativity of simultaneity, the influence of motion on measuring-rods and clocks, a modification of kinematics, and in particular a new theorem of addition of velocities. The second process supplies us with a modification of Newton’s law of motion for large velocities, together with information of fundamental importance on the nature of inertial mass. 中文

It was found that inertia is not a fundamental property of matter, nor,

indeed, an irreducible magnitude, but a property of energy. If an amount of energy E be given to a body, the inertial mass of the body increases by an amount E/c^2 , where c is the velocity of light *in vacuo*. On the other hand, a body of mass m is to be regarded as a store of energy of magnitude mc^2 . [中文](#)

Furthermore, it was soon found impossible to link up the science of gravitation with the special theory of relativity in a natural manner. In this connection I was struck by the fact that the force of gravitation possesses a fundamental property, which distinguishes it from electromagnetic forces. All bodies fall in a gravitational field with the same acceleration, or—what is only another formulation of the same fact—the gravitational and inertial masses of a body are numerically equal to each other. This numerical equality suggests identity in character. Can gravitation and inertia be identical? This question leads directly to the General Theory of Relativity. Is it not possible for me to regard the earth as free from rotation, if I conceive of the centrifugal force, which acts on all bodies at rest relatively to the earth, as being a “real” field of gravitation, or part of such a field? If this idea can be carried out, then we shall have proved in very truth the identity of gravitation and inertia. For the same property which is regarded as *inertia* from the point of view of a system not taking part in the rotation can be interpreted as *gravitation* when considered with respect to a system that shares the rotation. According to Newton, this interpretation is impossible, because by Newton’s law the centrifugal field cannot be regarded as being produced by matter, and because in Newton’s theory there is no place for a “real” field of the “Koriolis-field” type. But perhaps Newton’s law of field could be replaced by another that fits in with the field which holds with respect to a “rotating” system of coordinates? My conviction of the identity of inertial and gravitational mass aroused within me the feeling of absolute confidence in the correctness of this interpretation. In this connection I gained encouragement from the following idea. We are

familiar with the “apparent” fields which are valid relatively to systems of coordinates possessing arbitrary motion with respect to an inertial system. With the aid of these special fields we should be able to study the law which is satisfied in general by gravitational fields. In this connection we shall have to take account of the fact that the ponderable masses will be the determining factor in producing the field, or, according to the fundamental result of the special theory of relativity, the energy density—a magnitude having the transformational character of a tensor. [中文](#)

On the other hand, considerations based on the metrical results of the special theory of relativity led to the result that Euclidean metrics can no longer be valid with respect to accelerated systems of coordinates. Although it retarded the progress of the theory several years, this enormous difficulty was mitigated by our knowledge that Euclidean metrics holds for small domains. As a consequence, the magnitude ds , which was physically defined in the special theory of relativity hitherto, retained its significance also in the general theory of relativity. But the coordinates themselves lost their direct significance, and degenerated simply into numbers with no physical meaning, the sole purpose of which was the numbering of the space-time points. Thus in the general theory of relativity the coordinates perform the same function as the Gaussian coordinates in the theory of surfaces. A necessary consequence of the preceding is that in such general coordinates the measurable magnitude ds must be capable of representation in the form

$$ds^2 = \sum_{uv} g_{uv} dx_u dx_v ,$$

where the symbols g_{uv} are functions of the space-time coordinates. From the above it also follows that the nature of the space-time variation of the factors g_{uv} determines, on one hand the space-time metrics, and on the other the gravitational field which governs the mechanical behaviour of material points. [中文](#)

The law of the gravitational field is determined mainly by the following conditions: First, it shall be valid for an arbitrary choice of the system of coordinates; secondly, it shall be determined by the energy tensor of matter; and thirdly, it shall contain no higher differential coefficients of the factors g_{uv} than the second, and must be linear in these. In this way a law was obtained which, although fundamentally different from Newton's law, corresponded so exactly to the latter in the deductions derivable from it that only very few criteria were to be found on which the theory could be decisively tested by experiment. 中文

The following are some of the important questions which are awaiting solution at the present time. Are electrical and gravitational fields really so different in character that there is no formal unit to which they can be reduced? Do gravitational fields play a part in the constitution of matter, and is the continuum within the atomic nucleus to be regarded as appreciably non-Euclidean? A final question has reference to the cosmological problem. Is inertia to be traced to mutual action with distant masses? And connected with the latter: Is the spatial extent of the universe finite? It is here that my opinion differs from that of Eddington. With Mach, I feel that an affirmative answer is imperative, but for the time being nothing can be proved. Not until a dynamical investigation of the large systems of fixed stars has been performed from the point of view of the limits of validity of the Newtonian law of gravitation for immense regions of space will it perhaps be possible to obtain eventually an exact basis for the solution of this fascinating question. 中文

(106, 782-784; 1921)

相对论发展概述*

爱因斯坦

爱因斯坦的相对论在1921年得到了大家的广泛认可。在这篇演讲稿中，爱因斯坦从物理学力图摆脱超距作用的影响开始，对这个理论的历史沿革进行了回顾。麦克斯韦的电磁理论完成了这一使命，其他物理学家根据他的数学公式提出了以太假说，即认为所有的空间中都充满了作为电场和磁场媒介的以太。这使相对性原理遇到了困难，而爱因斯坦通过放弃事件的同时性可能与观测者的运动无关的观点摆脱了这个困境。但是这种新的理解没有考虑到重力。爱因斯坦猜测重力和惯性可能具有同一性，这一构想促使他提出了广义相对论。爱因斯坦设想重力和电现象或许也可以用一种适用于所有自然力的理论统一起来，这也是今天的物理学家们正在寻找的理论。

英文

用尽可能简练的语言来阐述一系列观念的演变，但仍充分完整地把这种演变的连续性保留下来，这是一件很吸引人的事。在讲述相对论的发展时，我们将尽力做到这一点，并说明其整个发展过程是由一系列细微而又不言而喻的思维过程构成的。

英文

整个发展历程始于并受制于法拉第和麦克斯韦的观念，按照他们的观念，所有的物理过程都包含连续作用（与超距作用相反），或者用数学语言来表示就是利用偏微分方程来描述物理过程。麦克斯韦利用真空位移电流的磁效应概念以及感生电动力场和静电场在本质上完全相同这一假定，成功地构筑了描述静止介质中电磁过程的偏微分方程。

英文

文

把电动力学理论推广到运动物体的重任落在了麦克斯韦的后继者的身上。赫兹试图通过赋予虚空（以太）与一般有重物质颇类似的物理性

质来解决这个问题。特别是，与有重物质一样，以太在空间的每一点上都应该有确定的速度。正如静止物体那样，如果电流或磁流的变化速度是以随物体一起运动的曲面元作为参考的话，那么电磁感应或者磁感应应当分别由电流或磁流的变化率决定。但是赫兹的理论及斐索有关光在流动液体中传播的基本实验相矛盾。就是说，麦克斯韦理论对运动物体的这种最直接的推广与实验结果不符。 [英文](#)

正在这时，洛伦兹进行了补救。由于洛伦兹是物质原子理论的忠实支持者，所以他觉得不能把物质看成是连续电磁场的所在地。因此，他设想这些场是连续的以太的某种状态。洛伦兹认为，从力学和物理学两方面的观点来看，以太在本质上与物质无关。以太不参与物质的运动，以太和物质之间的相互关系仅在于，物质被看成是所附电荷的载体。洛伦兹理论的重要价值在于，它使包括静止物体和运动物体在内的整个电动力学回归到了真空中的麦克斯韦方程。该理论不仅在方法论上超越了赫兹的理论，而且洛伦兹还利用它非常成功地解释了许多实验事实。

[英文](#)

这个理论似乎仅仅在一个重要的基本点上不能令人满意。这就是，似乎某个具有特殊运动状态的坐标系（它相对于以太是静止的）要比相对于这个坐标系运动的所有其他坐标系更加优越。从这一点上来看，这个理论好像违背了经典力学，因为在经典力学中，所有相互间做匀速运动的惯性系都同样有理由被用来当作坐标系（狭义相对性原理）。在这一点上，包括电动力学领域在内的所有经验（尤其是迈克尔逊实验）都支持所有惯性系均等价这一观点，即都支持狭义相对性原理。 [英文](#)

狭义相对论就是为解决这一困难而诞生的，这个困难由于它具有的根本性而无法让人容忍。狭义相对论最初被用于解答下述问题：狭义相对性原理真的与真空中的麦克斯韦场方程矛盾吗？答案似乎是肯定的。因为，如果某些方程对于坐标系K是成立的，而且我们引进一个新的坐标系K'，使它符合于（显然容易做到）如下的变换方程：

$$\left. \begin{aligned} x' &= x - vt \\ y' &= y \\ z' &= z \\ t' &= t \end{aligned} \right\} \text{ (伽利略变换),}$$

那么麦克斯韦场方程组在新的坐标系 (x', y', z', t') 中不再成立。但表面现象是靠不住的，在更透彻地分析时间和空间的物理意义后发现，伽利略变换是建立在几个相当任意的假设上面的，尤其是假设同时性的陈述与所使用的坐标系的运动状态无关。研究表明，如果我们利用下面的变换方程，则真空中的场方程可以满足狭义相对性原理：

$$\left. \begin{aligned} x' &= \frac{x - vt}{\sqrt{1 - v^2/c^2}} \\ y' &= y \\ z' &= z \\ t' &= \frac{t - vx/c^2}{\sqrt{1 - v^2/c^2}} \end{aligned} \right\} \text{ (洛伦兹变换)}$$

在上述方程中 x 、 y 、 z 表示位置坐标，用相对于坐标系静止的量尺来测量； t 表示时间，用处于静止状态的经过适当校准并且具有相同构造的时钟来测量。 [英文](#)

现在，为了使狭义相对性原理成立，要求所有的物理方程在使用洛伦兹变换来计算它们从一个惯性系到另一个惯性系的转换时其形式保持不变。用数学语言来描述就是，所有描述物理定律的方程相对于洛伦兹变换必须是协变的。因此，从方法论的角度来看，狭义相对性原理可以与第二种永恒运动不能实现的卡诺定理相比拟，因为正如卡诺定理一样，狭义相对性原理为我们提供了所有自然规律必须遵守的一般法则。

[英文](#)

随后，闵可夫斯基找到了一个特别简洁而又极具启发性的方式来表述这个协变条件，揭示了三维欧几里德几何学与物理学中时空连续统之间的对应关系。 [英文](#)

三维欧几里德几何学	狭义相对论
对应于空间中两个相邻的点，存在一种按如下方程计算的数值度量（距离 ds ）： $ds^2 = dx_1^2 + dx_2^2 + dx_3^2$	对应于时空中两个相邻的点（点事件），存在一种按如下方程计算的数值度量（距离 ds ）： $ds^2 = dx_1^2 + dx_2^2 + dx_3^2 + dx_4^2$
该距离与所选的坐标系无关，并可以用单位量尺测量。	该距离与所选择的惯性系无关，并可以用单位量尺和标准时钟测量。这里的 x_1, x_2, x_3 是直角坐标系中的坐标，而 $x_4 = \sqrt{-1}ct$ 是时间和虚数单位以及光速的乘积。
保持 ds^2 表达式不变的变换是允许的，即线性正交变换是允许的。	保持 ds^2 表达式不变的变换是允许的，即那些线性正交变换是允许的，它们保持了 x_1, x_2, x_3, x_4 表面上的实数性，这些变换就是洛伦兹变换。
相对于这些变换，欧几里德几何学中的定律保持不变。	相对于这些变换，物理学中的定律保持不变。

英文

由此可以看出，时间坐标在物理方程中的作用与空间坐标等价（除了实数性之外），虽然不是就其物理意义而言。按照这种观点，物理学过去和现在都是一种四维欧几里德几何学，或者，更确切地说，是四维欧几里德连续统中的一种静力学。

英文

狭义相对论的发展经历了两个主要阶段，这就是使时空“度规”适合于麦克斯韦电动力学，以及使物理学中的其余部分适合于这个新的时空“度规”。第一个阶段的成果有同时性的相对性、运动对量尺及时钟的影响、运动学的修正，特别是还有新的速度相加定理。第二个阶段给我们提供了在高速情况下对牛顿运动定律的修正，以及关于惯性质量本质的具有基本重要性的知识。

英文

研究表明惯性不是物质的基本属性，也不是一个不能分解的基本量，而只是能量的一个属性。如果我们赋予一个物体大小为 E 的能量，则此物体的惯性质量将增加 E/c^2 ，这里 c 是光在真空中的传播速度。同样，一个质量为 m 的物体将被认为具有 mc^2 的能量。

英文

此外，我们很快发现很难把引力科学同狭义相对论以自然的方式联系起来。这种情况使我意识到引力具有一种不同于电磁力的基本性质。在引力场中，所有物体都以相同的加速度下落，或者说，一个物体的引力质量和惯性质量在数值上是相等的（这只不过是同一个事实的另一种表达方式）。这种数值上的相同暗示着两者本质上的等同。引力和惯性能够等同吗？这个问题直接导致了广义相对论的产生。如果我把作用于所有相对于地球静止的物体上的离心力想象成是一个“真实的”引力场，或者是这种引力场的一部分，那我难道不能认为地球是不转动的吗？如

果这个想法能够实现，那么我们已经真正证明了引力和惯性的等同性。在不随地球转动的参考系里看来是惯性的这一特性，在随地球一起转动的参考系里可以被解释为引力。按照牛顿的观点，这样的解释是说不通的，因为牛顿定律告诉我们，离心力场不能被看作是由物质产生的，而且因为在牛顿的理论中，没有把“科里奥利场”这种类型的场当成是“真实的”场。但是，或许牛顿的有关场的定律可以用场的另外一种定律取代，这种定律既适合于这种场又在“转动”坐标系中成立？我坚信惯性质量与引力质量的等同性，这使我有绝对的信心认为上述解释是正确的。就这一点来说，我从以下观点中受到了鼓舞。我们熟悉“表观的”场，这些场在那些相对于一个惯性系做任意运动的坐标系中是有效的。借助于这些特殊的场，我们应当有可能研究引力场通常所满足的定律。关于这一点，我们不得不考虑这样的事实，即有重物质是产生场的决定性因素。或者可以这样表达，按照狭义相对论的基本结果，能量密度这个具有张量变换特性的物理量是产生场的决定因素。 [英文](#)

另一方面，基于对狭义相对论度规结果的考虑导致了这样的结论，即欧几里德度规不再适用于加速参考系。尽管它使理论的进程延迟了几十年，但是这个巨大的困难在我们认识到欧几里德度规对于小的区域依然适用之后就变得比较容易解决了。结果， ds 这个迄今在狭义相对论中定义的物理量，在广义相对论中其物理含义仍保持不变。但是坐标本身失去了直接的意义，而完全退化成没有物理意义的数字，它们的唯一用途是标记时空点，因此广义相对论中的坐标与曲面论中高斯坐标的作用相同。以上的叙述必然给出这样一个结论：可测量的量 ds 必定可以用这种广义坐标表达为以下形式：

$$ds^2 = \sum_{uv} g_{uv} dx_u dx_v,$$

这里符号 g_{uv} 是时空坐标的函数。以上的分析还表明，因子 g_{uv} 随时空变化的特性，一方面决定了时空度规，另一方面还决定了支配质点力学行为的引力场。 [英文](#)

引力场的定律主要取决于以下几个条件：第一，它应该在任意选择的坐标系中都是有效的；第二，它应当由物质的能量张量决定；第三，它所包含的因子 g_{uv} 的微分系数最高不超过二阶，并且它相对于这些微分

都是线性的。这样我们就得到了一个定律，虽然它在本质上不同于牛顿定律，但是在由它给出的推论中它与牛顿定律吻合得很好，以至于发现只有很少几个判据能够用来对它进行决定性的实验检验。 [英文](#)

下面是一些目前尚待解决的重要问题。电场和引力场在特性上真的有那么不同以至于不能用一个形式上的统一把它们都包含进去吗？引力场对物质的结构起一定作用吗？原子核内部的连续统在相当程度上可以被看作是非欧氏的吗？最后一个问题涉及到宇宙论，即惯性是否源自于远距离物质之间的相互作用？与后者相关的是：宇宙的空间范围是有限的吗？在这一点上我的观点和爱丁顿的观点相悖。与马赫一样，我感到迫切需要一个肯定的答案，但暂时还找不到证据证明。只有从这样的观点（即认为在广袤宇宙空间使用牛顿引力定律具有局限性的观点）出发来对庞大恒星系的动力学进行研究之后，才有可能最终获得解决这一令人困惑的问题的确切依据。 [英文](#)

（王锋 翻译；张元仲 审稿）

* 由罗伯特·劳森博士翻译。

Atomic Structure

N. Bohr

Here Danish physicist Niels Bohr ponders the possibility of explaining atomic properties on the basis of the new quantum theory. Physicists had conjectured about how the grouping of elements in the periodic table might reflect specific patterns of electrons arranged around the nucleus, yet without explaining how such patterns arise. As Bohr notes, his model of the hydrogen atom suggested that electrons may fall into distinct shells. Much of the periodic table, says Bohr, can be understood as the successive filling of these shells. The stability of filled shells would explain the chemical inactivity of inert gases such as helium and argon. Bohr's model was supplanted by a more mathematically rigorous quantum theory, yet much of his qualitative picture remains intact today. [中文](#)

IN a letter to *Nature* of November 25 last Dr. Norman Campbell discusses the problem of the possible consistency of the assumptions about the motion and arrangement of electrons in the atom underlying the interpretation of the series spectra of the elements based on the application of the quantum theory to the nuclear theory of atomic structure, and the apparently widely different assumptions which have been introduced in various recent attempts to develop a theory of atomic constitution capable of accounting for other physical and chemical properties of the elements. Dr. Campbell puts forward the

interesting suggestion that the apparent inconsistency under consideration may not be real, but rather appear as a consequence of the formal character of the principles of the quantum theory, which might involve that the pictures of atomic constitution used in explanations of different phenomena may have a totally different aspect, and nevertheless refer to the same reality. In this connection he directs attention especially to the so-called “principle of correspondence”, by the establishment of which it has been possible— notwithstanding the fundamental difference between the ordinary theory of electromagnetic radiation and the ideas of the quantum theory—to complete certain deductions based on the quantum theory by other deductions based on the classical theory of radiation. 中

文

In so far as it must be confessed that we do not possess a complete theory which enables us to describe in detail the mechanism of emission and absorption of radiation by atomic systems, I naturally agree that the principle of correspondence, like all other notions of the quantum theory, is of a somewhat formal character. But, on the other hand, the fact that it has been possible to establish an intimate connection between the spectrum emitted by an atomic system— deduced according to the quantum theory on the assumption of a certain type of motion of the particles of the atom—and the constitution of the radiation, which, according to the ordinary theory of electromagnetism, would result from the same type of motion, appears to me do afford an argument in favour of the reality of the assumptions of the spectral theory of a kind scarcely compatible with Dr. Campbell’s suggestion. On the contrary, if we admit the soundness of the quantum theory of spectra, the principle of correspondence would seem to afford perhaps the strongest inducement to seek an interpretation of the other physical and chemical properties of the elements on the same lines as the interpretation of their series spectra; and in this letter I should like briefly to indicate how it seems possible

by an extended use of this principle to overcome certain fundamental difficulties hitherto involved in the attempts to develop a general theory of atomic constitution based on the application of the quantum theory to the nucleus atom. [中文](#)

The common character of theories of atomic constitution has been the endeavour to find configurations and motions of the electrons which would seem to offer an interpretation of the variations of the chemical properties of the elements with the atomic number as they are so clearly exhibited in the well-known periodic law. A consideration of this law leads directly to the view that the electrons in the atom are arranged in distinctly separate groups, each containing a number of electrons equal to one of the periods in the sequence of the elements, arranged according to increasing atomic number. In the first attempts to obtain a definite picture of the configuration and motion of the electrons in these groups it was assumed that the electrons within each group at any moment were placed at equal angular intervals on a circular orbit with the nucleus at the centre, while in later theories this simple assumption has been replaced by the assumptions that the configurations of electrons within the various groups do not possess such simple axial symmetry, but exhibit a higher degree of symmetry in space, it being assumed, for instance, that the configuration of the electrons at any moment during their motions possesses polyhedral symmetry. All such theories involve, however, the fundamental difficulty that no interpretation is given why these configurations actually appear during the formation of the atom through a process of binding of the electrons by the nucleus, and why the constitution of the atom is essentially stable in the sense that the original configuration is reorganized if it be temporarily disturbed by external agencies. If we reckon with no other forces between the particles except the attraction and repulsion due to their electric charges, such an interpretation claims clearly that there must exist an intimate interaction or “coupling” between the various groups of electrons in

the atom which is essentially different from that which might be expected if the electrons in different groups are assumed to move in orbits quite outside each other in such a way that each group may be said to form a “shell” of the atom, the effect of which on the constitution of the outer shells would arise mainly from the compensation of a part of the attraction from the nucleus due to the charge of the electrons. [中文](#)

These considerations are seen to refer to essential features of the nucleus atom, and so far to have no special relation to the character of the quantum theory, which was originally introduced in atomic problems in the hope of obtaining a rational interpretation of the stability of the atom. According to this theory an atomic system possesses a number of distinctive states, the co-called “stationary states”, in which the motion can be described by ordinary mechanics, and in which the atom can exist, at any rate for a time, without emission of energy radiation. The characteristic radiation from the atom is emitted only during a transition between two such states, and this process of transition cannot be described by ordinary mechanics, any more than the character of the emitted radiation can be calculated from the motion by the ordinary theory of electro-magnetism, it being, in striking contrast to this theory, assumed that the transition is always followed by an emission of monochromatic radiation the frequency of which is determined simply from the difference of energy in the two states. The application of the quantum theory to atomic problems—which took its starting point from the interpretation of the simple spectrum of hydrogen, for which no *a priori* fixation of the stationary states of the atoms was needed—has in recent years been largely extended by the development of systematic methods for fixing the stationary states corresponding to certain general classes of mechanical motions. While in this way a detailed interpretation of spectroscopic results of a very different kind has been obtained, so far as phenomena which depend essentially on the motion of one electron

in the atom were concerned, no definite elucidation has been obtained with regard to the constitution of atoms containing several electrons, due to the circumstance that the methods of fixing stationary states were not able to remove the arbitrariness in the choice of the number and configurations of the electrons in the various groups, or shells, of the atom. In fact, the only immediate consequence to which they lead is that the motion of every electron in the atom will on a first approximation correspond to one of the stationary states of a system consisting of a particle moving in a central field of force, which in their limit are represented by the various circular or elliptical stationary orbits which appear in Sommerfeld's theory of the fine structure of the hydrogen lines. A way to remove the arbitrariness in question is opened, however, by the introduction of the correspondence principle, which gives expression to the tendency in the quantum theory to see not merely a set of formal rules for fixing the stationary states of atomic systems and the frequency of the radiation emitted by the transitions between these states, but rather an attempt to obtain a rational generalization of the electromagnetic theory of radiation which exhibits the discontinuous character necessary to account for the essential stability of atoms. [中文](#)

Without entering here on a detailed formulation of the correspondence principle, it may be sufficient for the present purpose to say that it establishes an intimate connection between the character of the motion in the stationary states of an atomic system and the possibility of a transition between two of these states, and therefore offers a basis for a theoretical examination of the process which may be expected to take place during the formation and reorganisation of an atom. For instance, we are led by this principle directly to the conclusion that we cannot expect in actual atoms configurations of the type in which the electrons within each group are arranged in rings or configurations of polyhedral symmetry, because the formation of such configurations would claim that all the electrons within each group

should be originally bound by the atom at the same time. On the contrary, it seems necessary to seek the configurations of the electrons in the atoms among such configurations as may be formed by the successive binding of the electrons one by one, a process the last stages of which we may assume to witness in the emission of the series spectra of the elements. Now on the correspondence principle we are actually led to a picture of such a process which not only affords a detailed insight into the structure of these spectra, but also suggests a definite arrangement of the electrons in the atom of a type which seems suitable to interpret the high-frequency spectra and the chemical properties of the elements. Thus from a consideration of the possible transitions between stationary states, corresponding to the various steps of the binding of each of the electrons, we are led in the first place to assume that only the two first electrons move in what may be called one-quantum orbits, which are analogous to that stationary state of a central system which corresponds to the normal state of a system consisting of one electron rotating round a nucleus. The electrons bound after the first two will not be able by a transition between two stationary states to procure a position in the atom equivalent to that of these two electrons, but will move in what may be called multiple-quanta orbits, which correspond to other stationary states of a central system. [中文](#)

The assumption of the presence in the normal state of the atom of such multiple-quanta orbits has already been introduced in various recent theories, as, for instance, in Sommerfeld's work on the high-frequency spectra and in that of Landé on atomic dimensions and crystal structure; but the application of the correspondence principle seems to offer for the first time a rational theoretical basis for these conclusions and for the discussion of the arrangement of the orbits of the electrons bound after the first two. Thus by means of a closer examination of the progress of the binding process this principle offers a simple argument for concluding that these electrons are arranged in

groups in a way which reflects the periods exhibited by the chemical properties of the elements within the sequence of increasing atomic numbers. In fact, if we consider the binding of a large number of electrons by a nucleus of high positive charge, this argument suggests that after the first two electrons are bound in one-quantum orbits, the next eight electrons will be bound in two-quanta orbits, the next eighteen in three-quanta orbits, and the next thirty-two in four-quanta orbits. [中文](#)

Although the arrangements of the orbits of the electrons within these groups will exhibit a remarkable degree of spatial symmetry, the groups cannot be said to form simple shells in the sense in which this expression is generally used as regards atomic constitution. In the first place, the argument involves that the electrons within each group do not all play equivalent parts, but are divided into sub-groups corresponding to the different types of multiple-quanta orbits of the same total number of quanta, which represents the various stationary states of an electron moving in a central field. Thus, corresponding to the fact that in such a system there exist two types of two-quanta orbits, three types of three-quanta orbits, and so on, we are led to the view that the above-mentioned group of eight electrons consists of two sub-groups of four electrons each, the group of eighteen electrons of three sub-groups of six electrons each, and the group of thirty-two electrons of four sub-groups of eight electrons each. [中文](#)

Another essential feature of the constitution described lies in the configuration of the orbits of the electrons in the different groups relative to each other. Thus for each group the electrons within certain sub-groups will penetrate during their revolution into regions which are closer to the nucleus than the mean distances of the electrons belonging to groups of fewer-quanta orbits. This circumstance, which is intimately connected with the essential features of the processes of successive binding, gives just that

expression for the “coupling” between the different groups which is a necessary condition for the stability of atomic configurations. In fact, this coupling is the predominant feature of the whole picture, and is to be taken as a guide for the interpretation of all details as regards the formation of the different groups and their various sub-groups. Further, the stability of the whole configuration is of such a character that if any one of the electrons is removed from the atom by external agencies not only may the previous configuration be reorganised by a successive displacement of the electrons within the sequence in which they were originally bound by the atom, but also the place of the removed electron may be taken by any one of the electrons belonging to more loosely bound groups or sub-groups through a process of direct transition between two stationary states, accompanied by an emission of a monochromatic radiation. This circumstance—which offers a basis for a detailed interpretation of the characteristic structure of the high-frequency spectra of the elements—is intimately connected with the fact that the electrons in the various sub-groups, although they may be said to play equivalent parts in the harmony of the inter-atomic motions, are not at every moment arranged in configurations of simple axial or polyhedral symmetry as in Sommerfeld’s or Landé’s work, but that their motions are, on the contrary, linked to each other in such a way that it is possible to remove any one of the electrons from the group by a process whereby the orbits of the remaining electrons are altered in a continuous manner. [中文](#)

These general remarks apply to the constitution and stability of all the groups of electrons in the atom. On the other hand, the simple variations indicated above of the number of electrons in the groups and sub-groups of successive shells hold only for that region in the atom where the attraction from the nucleus compared with the repulsion from the electrons possesses a preponderant influence on the motion of each electron. As regards the arrangements of the electrons

bound by the atom at a moment when the charges of the previously bound electrons begin to compensate the greater part of the positive charge of the nucleus, we meet with new features, and a consideration of the conditions for the binding process forces us to assume that new, added electrons are bound in orbits of a number of quanta equal to, or fewer than, that of the electrons in groups previously bound, although during the greater part of their revolution they will move outside the electrons in these groups. Such a stop in the increase, or even decrease, in the number of quanta characterising the orbits corresponding to the motion of the electrons in successive shells takes place, in general, when somewhat more than half the total number of electrons is bound. During the progress of the binding process the electrons will at first still be arranged in groups of the indicated constitution, so that groups of three-quanta orbits will again contain eighteen electrons and those of two-quanta orbits eight electrons. In the neutral atom, however, the electrons bound last and most loosely will, in general, not be able to arrange themselves in such a regular way. In fact, on the surface of the atom we meet with groups of the described constitution only in the elements which belong to the family of inactive gases, the members of which from many points of view have also been acknowledged to be a sort of landmark within the natural system of the elements. For the atoms of these elements we must expect the constitutions indicated by the following symbols:

Helium	(2 ₁),	Krypton	(2 ₁ 8 ₂ 18 ₃ 8 ₂),
Neon	(2 ₁ 8 ₂)	Xenon	(2 ₁ 8 ₂ 18 ₃ 18 ₃ 8 ₂),
Argon	(2 ₁ 8 ₂ 8 ₂),	Niton*	(2 ₁ 8 ₂ 18 ₃ 32 ₄ 18 ₃ 8 ₂),

* "Niton" was the provisional name in 1921 for the radioactive gas now called "radon".

where the large figures denote the number of electrons in the groups starting from the innermost one, and the small figures the total number of quanta characterising the orbits of electrons within each group. 中文

These configurations are distinguished by an inherent stability in the

sense that it is especially difficult to remove any of the electrons from such atoms so as to form positive ions, and that there will be no tendency for an electron to attach itself to the atom and to form a negative ion. The first effect is due to the large number of electrons in the outermost group; hence the attraction from the nucleus is not compensated to the same extent as in configurations where the outer group consists only of a few electrons, as is the case in those families of elements which in the periodic table follow immediately after the elements of the family of the inactive gases, and, as is well known, possess a distinct electro-positive character. The second effect is due to the regular constitution of the outermost group, which prevents a new electron from entering as a further member of this group. In the elements belonging to the families which in the periodic table precede the family of the inactive gases we meet in the neutral atom with configurations of the outermost group of electrons which, on the other hand, exhibit a great tendency to complete themselves by the binding of further electrons, resulting in the formation of negative ions. 中

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The general lines of the latter considerations are known from various recent theories of atomic constitution, such as those of A. Kossel and G. Lewis, based on a systematic discussion of chemical evidence. In these theories the electro-positive and electro-negative characters of these families in the periodic table are interpreted by the assumption that the outer electrons in the atoms of the inactive gases are arranged in especially regular and stable configurations, without, however, any attempt to give a detailed picture of the constitution and formation of these groups. In this connection it may be of interest to direct attention to the fundamental difference between the picture of atomic constitution indicated in this letter and that developed by Langmuir on the basis of the assumption of stationary or oscillating electrons in the atom, referred to in Dr. Campbell's letter. Quite apart from the fact that in Langmuir's theory the stability of the configuration of the

electrons is considered rather as a postulated property of the atom, for which no detailed *a priori* interpretation is offered, this difference discloses itself clearly by the fact that in Langmuir's theory a constitution of the atoms of the inactive gases is assumed in which the number of electrons is always largest in the outermost shell. Thus the sequence of the number of electrons within the groups of a niton atom is, instead of that indicated above, assumed to be 2, 8, 18, 18, 32, such as the appearance of the periods in the sequence of the elements might seem to claim at first sight. 中文

The assumption of the presence of the larger groups in the interior of the atom, which is an immediate consequence of the argument underlying the present theory, appears, however, to offer not merely a more suitable basis for the interpretation of the general properties of the elements, but especially an immediate interpretation of the appearance of such families of elements within the periodic table, where the chemical properties of successive elements differ only very slightly from each other. The existence of such families appears, in fact, as a direct consequence of the formation of groups containing a larger number of electrons in the interior of the atom when proceeding through the sequence of the elements. Thus in the family of the rare earths we may be assumed to be witnessing the successive formation of an inner group of thirty-two electrons at that place in the atom where formerly the corresponding group possessed only eighteen electrons. In a similar way we may suppose the appearance of the iron, palladium, and platinum families to be witnessing stages of the formation of groups of eighteen electrons. Compared with the appearance of the family of the rare earths, however, the conditions are here somewhat more complicated, because we have to do with the formation of a group which lies closer to the surface of the atom, and where, therefore, the rapid increase in the compensation of the nuclear charge during the progress of the binding process plays a greater part. In fact, we have to do in the cases in question, not, as in

the rare earths, with a transformation which in its effects keeps inside one and the same group, and where, therefore, the increase in the number in this group is simply reflected in the number of the elements within the family under consideration, but we are witnesses of a transformation which is accompanied by a confluence of several outer groups of electrons. [中文](#)

In a fuller account which will be published soon the questions here discussed will be treated in greater detail. In this letter it is my intention only to direct attention to the possibilities which the elaboration of the principles underlying the spectral applications of the quantum theory seems to open for the interpretation of other properties of the elements. In this connection I should also like to mention that it seems possible, from the examination of the change of the spectra of the elements in the presence of magnetic fields, to develop an argument which promises to throw light on the difficulties which have hitherto been involved in the explanation of the characteristic magnetic properties of the elements, and have been discussed in various recent letters in *Nature*. [中文](#)

(107, 104-107; 1921)

N. Bohr: Copenhagen, February 14.

原子结构

玻尔

在这篇文章中丹麦物理学家尼尔斯·玻尔反复思索是否可以用新的量子理论来解释原子的性质。物理学家们猜测周期表中的元素分组可能在某种程度上反映了核外电子的排布情况，但没有说明这种排布模式是如何形成的。玻尔指出，他的氢原子模型可以说明电子为什么会填入不同的壳层。玻尔说，周期表中大部分元素的核外电子都可以被认为是连续填充这些壳层的。充满电子的壳层结构比较稳定，因而表现出化学反应上的惰性，如氦、氩等惰性气体。虽然玻尔模型已经被数学上更为严密的量子理论取代，但他对核外电子排布的大部分定性描述至今仍然有效。 [英文](#)

诺曼·坎贝尔博士在去年11月25日写给《自然》的信中，谈到有关原子中电子运动和排布的假说是否可能保持前后一致的问题，这关系到量子理论能否作为原子结构的核心理论对一系列元素的光谱进行解释的问题，为了建立一个能够解释元素其他物理化学性质的原子组成理论，人们在最近的研究中提出了许多差异很大的假设。坎贝尔博士的观点令人振奋，他提出，表面上的矛盾可能不是真的，而是因为量子理论的原理具有表观化的特征，其对原子构成的描述用于解释不同的现象时可能使用完全不同的形式。他把人们对这个问题的注意力转向了所谓的“对应原理”，尽管普通电磁辐射理论与量子理论存在本质上的不同，但在建立了“对应原理”之后，就可能可以用经典辐射理论的结论推导出量子力学理论中的某些推论。 [英文](#)

必须承认，我们至今尚未建立起一个完整的理论来详细地描述原子系统发射辐射和吸收辐射的机制，我当然同意“对应原理”像所有其他的量子理论概念一样，在某种意义上也带有形式化的特征。但是，从另一

个角度上说，现在已经有可能在一个原子系统——根据基于假设原子中的粒子做某种形式的运动的量子理论推导得到——的发射光谱和由同样类型的运动产生的放射物的构成之间建立一种紧密的关系，根据普通的电磁学理论，我认为它提供了一个论点，这个论点支持一种与坎贝尔博士的建议几乎完全不相符的光谱理论假说。相反，如果我们承认用量子理论解释光谱是合理的，那么“对应原理”在解释元素的系列光谱以及元素的其他物理化学性质方面也许能够得出最可信的推论；在这封信中，我将简单地介绍当我们在试图把量子理论应用于原子核系统以构建一个普适的原子组成理论时，是如何广泛地运用这一原则来克服目前遇到的主要难题的。 [英文](#)

一系列原子组成理论的共性是都在极力寻找电子的排列和运动规律以解释元素的化学性质为什么会随原子序数的增加而发生周期性变化，正如众所周知的周期率明确指出的那样。周期率使人们猜想，原子中的电子可以被分为不同的组，每一组包括的电子数等于元素序列的一个周期。在早先试图明确描述各组中电子排布和运动的理论中，人们假设每一组中的电子在任一时刻都以相等的角间距排布在以原子核为中心的圆形轨道上，而在后来的理论中，这一简单的假设被新的假设取代，即认为各组中的电子排布不具有这种单一的轴对称，但在空间上则表现出更高等度的对称。例如，假设在电子运动的任一时刻它们的排布呈多面体对称。但是，所有这些理论都难以解释为什么通过原子核束缚电子而生成原子的过程中会出现这样的排布，也不能解释当外部介质暂时侵入时为什么原子的结构在原始排列重组后依然保持基本稳定。如果我们设想，除了由于所带电荷产生的吸引力或排斥力之外，粒子之间再无其他作用力，那么这样的解释就明确要求在原子中不同组的电子之间必须存在一种紧密的相互作用或“耦合”，这完全不同于认为各组电子运动轨道之间的距离也许远到足以使每一组电子单独形成原子的一个“壳层”的假设，耦合效应对外层电子的影响主要是部分地抵消由于电子带负电荷而受到的来自原子核的吸引力。 [英文](#)

上述论点被认为涉及到核原子的基本特征，与量子理论的特殊性没有关系，人们把量子理论引入原子体系的初衷是希望它能够对原子的稳定性给出合理的解释。根据量子理论，原子体系中存在若干种不同的状

态，即所谓的“定态”，电子在定态中的运动不能用一般理论来解释，在某一段时间内，原子可以以任意速率运动，但不会以辐射方式释放能量。只有在两个定态之间发生跃迁时原子才会发射特征辐射，而这种跃迁过程不能用一般理论来描述，更不用说利用普通的电磁理论根据运动规律计算发射的特征辐射了。与普通电磁理论形成鲜明的对照，量子理论假设跃迁通常伴随着发出单色辐射的过程，频率只取决于两个状态之间的能量差。最初应用量子理论解决原子中的问题是从解释简单的氢原子光谱开始的，因为氢原子不需要先验地确定定态，现在人们根据特定力学运动的类别已经得到了确定定态的系统化方法，因而量子力学理论已经被广泛地用于解决原子中的问题。虽然通过这种方式我们已经获得了许多差异很大的对光谱结果的详细解释，但只局限于研究原子中与单电子运动有关的现象。对于包括几个电子的原子，则由于确定定态的方法不能够排除在原子内不同组（或称壳层）中选择电子数量及其排布时的随意性，而无法得到明确的解释。实际上，这导致的唯一的直接后果是：原子中每个电子的运动情况都可以用一个在中心力场中运动的粒子的一个定态来近似，这种近似只限于用索末菲关于氢线精细结构理论中的圆形或椭圆形轨道来描述定态。但在引入了“对应原理”之后，人们就有了消除随意性的方法，这表明量子理论的发展趋势不仅在于建立一套正式的规则以确定原子体系中的定态和在这些定态之间发生跃迁时发射的辐射频率，而且还要努力总结出合理的辐射电磁理论法则，这一法则对不连续特性的解释必须能够说明原子是稳定的。 [英文](#)

在这里不用详述“对应原理”的具体内容，为了解决现在的矛盾，也许可以认为它足以在原子体系不同定态的运动特征与两个定态发生跃迁的可能性之间建立很强的相关性，因而为用理论检验一个原子形成或重组时可能发生的过程提供了依据。例如，根据这个原理我们得出的直接结论是：在实际原子中每一组电子的排布都不可能是环形也都不是多边形对称，因为形成这样的排布要求各组中所有的电子都必须在开始的时候同时被原子束缚住。恰恰相反，我们有必要在原子中寻找使电子有可能是一个一个连续地被原子束缚住的排布方式，我们也许能在元素系列发射光谱中观察到这个过程的最后阶段。现在利用“对应原理”，我们对该过程的描述不仅能够精确地解析这些光谱的结构，还能明确地提出原子中电子的排布方式，既适合解释高频光谱，又能说明元素的化学性

质。因此从考虑定态之间可能出现的跃迁入手，根据束缚每一个电子的不同步骤，我们首先假设只有最开始的2个电子在可以被称为1-量子的轨道上运动，1-量子轨道近似于一个中心体系的定态，即一个电子绕一个原子核旋转的体系的基准状态。在最开始的2个电子之后被束缚的电子将不能通过两个定态之间的跃迁进入原子中与最开始的2个电子等同的位置，但将在可以被称作多量子的轨道上运动，相当于一个中心体系中的其他定态。 [英文](#)

最近的一些理论已经假定过这样的多量子轨道存在于正常状态的原子中，如在索末菲关于高频光谱的论文中，以及在朗代关于原子大小和晶体结构的著作中；但正是对应原理第一次为这些推论提供了合理的理论依据，也为在最开始的2个电子之后被束缚的电子轨道如何分配这一问题提供了解答。因此通过对束缚过程的进一步研究，对应原理提出了一个简单的规则，认为这些电子分组排列的方式也是元素化学性质随原子序数递增而表现出周期性的反映。实际上，如果我们考虑的是大量电子被一个带较多正电荷的原子核束缚，该规则指出：最开始的2个电子位于1-量子轨道，后8个电子被束缚于2-量子轨道，然后18个电子在3-量子轨道，再后面32个电子位于4-量子轨道。 [英文](#)

尽管各组中电子轨道的排列呈现出惊人的空间对称性，但不能因此而认为这些组在原子构造上显示出大家普遍接受的简单壳层结构。首先，该规则认为，同一壳层中的电子并不都扮演同样的角色，总量子数相等的多量子轨道有不同的类型，对应于这些不同的类型，电子又被归入不同的子壳层，子壳层也是描绘电子在中心力场中运动的定态。因此，根据一个体系中存在2类2-量子轨道，3类3-量子轨道，以此类推，我们可以得到这样的结论——上面提到的8电子壳层由2个4电子子壳层构成，18电子壳层由3个6电子子壳层构成，32电子壳层由4个8电子子壳层构成。 [英文](#)

原子组成的另一个基本特征是：不同壳层中电子轨道的构型相互关联。因而对每一个壳层来说，其中某些子壳层中的电子在绕核旋转过程中会进入离核距离比量子数较低轨道（即更内层的轨道）中电子离核的平均距离更近的区域。该现象与连续成键过程的基本特征联系紧密，说明不同壳层之间存在“耦合”现象，这种耦合正是使原子构型保持稳定的

必要条件。事实上，这样的耦合是整个理论的主要特征，也是理解不同壳层及其子壳层结构所有细节的基础。另外，整个原子结构具有保持稳定特点——如果原子中的任何一个电子由于外界因素被移走，不仅被原子束缚的电子会在以前原子构型的基础上通过连续位移而进行重新组合，而且那些受束缚较弱的壳层或子壳层中的电子可以通过两个定态之间的直接跃迁而占据被移走的电子的位置，同时发出单色辐射。这个能为详细解释元素高频光谱特征结构提供依据的现象与以下的事实密切相关：尽管我们认为不同子壳层中的电子在原子内的简谐运动中起着同样的作用，但它们并非每时每刻都在外形上保持索末菲和朗代的著作中所说的简单轴对称或者多面体对称，相反，这些电子的行为是通过这样的方式相互联系的——当外力从壳层中移走任何一个电子后，其余电子的轨道将发生连续的变化。

英文

这些观点可用于解释原子中所有壳层电子的组成方式和稳定性。另外，在连续的壳层和子壳层中，上述电子数目的简单变化只会发生在原子中的某个区域，在这个区域内，原子核的吸引力对每个电子运动的影响远远大于电子之间的排斥力。考虑到之前被原子核束缚的电子的电荷开始抵消掉原子核的大部分正电荷时的电子排布情况，我们得到了一些新的观点，成键过程要求的条件使我们不得不假设新增电子所在轨道的量子数等于或小于以前该壳层被束缚的电子，尽管它们在绕原子核旋转的大部分时间内都在该壳层中其他电子的外侧运动。一般说来，表征连续壳层中电子运动状态的轨道量子数或许在一半以上的电子被束缚后就不再增减了。在成键过程中，电子仍会首先排布在确定结构的壳层中，因此3-量子轨道壳层还会有18个电子，而2-量子轨道壳层还会有8个电子。然而，在中性原子中，最后成键且受束缚最弱的电子通常不会按照这样的规则排布。事实上，在原子表层，我们仅在惰性气体元素中观察到上面描述的壳层结构，因此，从各方面看，惰性气体家族都可以称得上是人们认识天然元素体系的里程碑。我们料想这些元素的原子组成可以用符号表示如下：

氦 (2_1),

氦 ($2_1 8_2 18_3 8_2$),

氖 ($2_1 8_2$),

氖 ($2_1 8_2 18_3 18_3 8_2$),

氡 ($2_1 8_2 8_2$),

氡* ($2_1 8_2 18_3 32_4 18_3 8_2$),

* “Niton”是现在被称为“radon”的放射性气体在1921年的临时名称。

其中较大的数字代表从最内层开始每一壳层上的电子数，较小的数字代表每一壳层中电子轨道的总量子数。 [英文](#)

惰性气体的原子结构具有很强的内在稳定性，从某种意义上说，很难从这样的原子中移走任何一个电子使其变成正离子；同样，一个电子与这类原子结合而使其变成负离子也是不可能的。前者是由于最外层有大量的电子，因此对原子核吸引力的抵消程度大于那些外层只有较少电子的原子，如元素周期表中紧跟在惰性气体之后的那些元素，正如大家所知道的，这种结构具有明显的正电特性。后者是由于最外层电子的规则排列阻止了一个外来电子加入该壳层成为新成员。另一方面，我们发现在元素周期表中排在惰性气体之前的那些族的元素，它们的中性原子的最外层电子结构非常倾向于吸引外来电子以填满该壳层从而形成负离子。 [英文](#)

后面提到的种种看法都是根据最近关于原子组成的各种理论得到的，如科塞尔和刘易斯建立在化学实验系统分析基础上的理论。这些理论认为，如果假定惰性气体原子的外层电子结构非常规则和稳定，就可以理解为什么元素周期表中某些族的元素带有正电特性而另一些族的元素带有负电特性，但没有人试图对原子壳层的结构和成因给予详细解释。关于这一点也许更值得关注的是：本文中所阐述的原子结构理论与坎贝尔博士在来信中提到的朗缪尔的理论有本质的不同，朗缪尔假设电子在原子中处于定态或振荡态。本文提到的理论与朗缪尔的理论的不同之处在于：电子排布的稳定性被视为是原子的必要属性，但关于这一点没有给出详细的先验的解释，这种不同本身很明确地表明，朗缪尔的理论认为惰性气体原子的最外层电子数总是最大的。因此，氢原子每一壳层上的电子数不再是上文提到的，而是2、8、18、18、32，乍一看似乎在表面上仍然保留了元素的周期性。 [英文](#)

然而，作为当前理论的一个直接推论，原子内部存在较大壳层的假设不仅更适合于解释各种元素的一般性质，而且能马上解释元素周期表中为什么存在相邻元素的化学性质相差非常小的族。事实上，这些族的存在是因为随着原子序数的递增，增加的电子填充到了原子内部的可以容纳大量电子的壳层中。如此说来，我们也许可以认为在稀土族元素中，电子在最多可以容纳32个电子而原来仅含有18个电子的内壳层中连

续地填充。我们同样可以猜测到铁、钷、铂族元素是在逐步填充最多可容纳18个电子的壳层。然而，与稀土族相比，铁、钷、铂族元素的情况更复杂一些，因为在靠近原子表面的壳层填充电子时我们不得不面临的难题是，在成键过程中对核电荷的补偿的增加速度非常快。事实上，我们还必须用一种在同一壳层内部发生的转变来解决这些在稀土元素中不存在的难题，因此该壳层中电子数目的增加只是反映了被考虑的族中原子序数的增加，但是我们发现了伴随着几个外层电子汇合的转化过程。

英文

我在即将发表的报告中将更详细地说明这里提到的问题。我写这封信的目的只是让大家注意，应用量子理论解释光谱的那些基本原理的详细阐述，看起来也有可能同时解释了元素的其他性质。就此而言，我还想提醒大家，通过研究磁场中元素光谱的变化，也许可以提出一种有望解决迄今为止人们在解释元素磁特性时遇到的困难的观点，《自然》近期的几篇快报已经对此问题进行了讨论。

英文

（王锋 翻译；李淼 审稿）

The Dimensions of Atoms and Molecules

W. L. Bragg and H. Bell

In the early 1920s, physicists were struggling to understand the physical structure of atoms using a model introduced by Bohr in 1913, in which electrons filled up shells around the nucleus. Bohr's arguments predicted that elements within any particular period (row) of the periodic table should have roughly the same atomic size, but that atomic size should jump markedly when moving from one period to the next. Here Lawrence Bragg and H. Bell report data on the dimensions of atoms that support Bohr's ideas. Estimating these dimensions from crystal densities and liquid viscosity, they find that elements near the end of rows in the table have almost identical dimensions, while a definite increase happens from one period to the next. [中文](#)

CERTAIN relations which are to be traced between the distances separating atoms in a crystal make it possible to estimate the distance between their centres when linked together in chemical combination. On the Lewis-Langmuir theory of atomic constitution, two electro-negative elements when combined hold one or more pairs of electrons in common, so that the outer electron shell of one atom may be regarded as coincident with that of the other at the point where the atoms are linked together. From this point of view, estimates may be made (W. L. Bragg, *Phil. Mag.*, vol. XI, August, 1920) from crystal data

of the diameters of these outer shells. The outer shell of neon, for example, was estimated from the apparent diameters of the carbon, nitrogen, oxygen, and fluorine atoms, which show a gradual approximation to a minimum value of 1.30×10^{-8} cm. The diameters of the inert gases as found in this way are given in the second column of the following table:

Gas	Diameter 2σ (Crystals)	Diameter $2\sigma'$ (Viscosity)	Difference $2\sigma' - 2\sigma$
Helium	—	1.89	—
Neon	1.30	2.35	1.05
Argon	2.05	2.87	0.82
Krypton	2.35	3.19	0.84
Xenon	2.70	3.51	0.81

中文

In the third column are given Rankine’s values (A. O. Rankine, *Proc. Roy. Soc., A*, vol. XCVIII, 693, pp. 360–374, February, 1921) for the diameters of the inert gases calculated from their viscosities by Chapman’s formula (S. Chapman, *Phil. Trans. Roy. Soc., A*, vol. CCXVI, pp. 279–348, December, 1915). These are considerably greater than the diameters calculated from crystals, but this is not surprising in view of our ignorance both of the field of force surrounding the outer electron shells and of the nature of the electron-sharing which links the atoms together, for it is quite possible that their structures might coalesce to a considerable extent. The constancy of the differences between the two estimates given in the fourth column shows that the *increase* in the size of the atom as each successive electron shell is added is nearly the same (except in the case of neon), whether measured by viscosity or by the crystal data. Further, Rankine has shown that the molecule Cl_2 behaves as regards its viscosity like two argon atoms with a distance between their centres very closely equal to that calculated from crystals, and that the same is true for the pairs Br_2 and krypton, I_2 and xenon.

中文

We see, therefore, that the evidence both of crystals and viscosity measurements indicates that (a) the elements at the end of any one period in the periodic table are very nearly identical as regards the diameters of their outer electron shells, and (b) in passing from one period to the next there is a definite increase in the dimensions of the outer electron shell, the absolute amount of this increase estimated by viscosity agreeing closely with that determined from crystal measurements. [中文](#)

A further check on these measurements is afforded by the infra-red absorption spectra of HF, HCl, and HBr. The wave-number difference δv between successive absorption lines determines the moment of inertia I of the molecule in each case, the formula being

$$\delta v = \frac{h}{4\pi^2 c I} \, ,$$

where h is Planck’s constant and c the velocity of light. [中文](#)

It is therefore possible to calculate the distances between the centres of the nuclei in each molecule, for

$$s^2 = \frac{m + m'}{mm'} \cdot \frac{h}{4\pi^2 c m_H \delta v} \, ,$$

where m and m' are the atomic weights relative to hydrogen and m_H the mass of the hydrogen atom. The following table gives these distances (E. S. Imes, *Astroph. Journal*, vol. 1, p. 251, 1919). It will be seen that there are again increases in passing from F to Cl and Cl to Br, which agree closely with the increases in the radii σ of the electron shells given by the crystal and viscosity data. [中文](#)

$s \times 10^8$			$\sigma \times 10^8$ (Crystals)	$\sigma' \times 10^8$ (Viscosity)
HF	0.93	0.35 0.15	Neon (=F)	1.17
HCl	1.28		Argon (=Cl)	1.43
HBr	1.43		Krypton (=Br)	1.58
HI	—		Xenon (=I)	1.75

The increase from fluorine to chlorine of 0.35×10^{-8} cm confirms the estimate given by crystals of 0.37×10^{-8} cm, as against the estimate 0.26×10^{-8} cm given by viscosity data. It follows from the above that the distance between the hydrogen nucleus and the centre of an electro-negative atom to which it is attached is obtained by adding 0.26×10^{-8} cm to the radius of the electro-negative atom as given by crystal structures. The radius of the inner electron orbit, according to Bohr's theory, is 0.53×10^{-8} cm, double this value. The crystal data, therefore, predict the value $\delta\nu = 13.0 \text{ cm}^{-1}$ for the HI molecule, corresponding to a distance 1.61×10^{-8} cm between their atomic centres. 中文

This evidence is interesting as indicating that the forces binding the atoms together are localised at that part of the electron shell where linking takes place. 中文

(107, 107; 1921)

W. L. Bragg, H. Bell: Manchester University, March 16.

原子和分子的尺度

布拉格，贝尔

20世纪20年代初期的物理学家总想应用1913年玻尔提出的模型来努力理解原子的物理结构，在玻尔的模型中，电子填充原子核外的壳层。玻尔的理论预言，在周期表中任意一个周期（一行）的元素应该具有大致相同的原子尺寸，但是从一个周期变化到下一个周期时，原子的大小将发生显著的变化。在这篇文章中，劳伦斯·布拉格和贝尔列举了各种原子的尺寸数据，这些数据支持玻尔的理论。根据这些由晶体密度和液体粘度估算得到的数据，他们发现周期表中每行靠近行尾的元素具有几乎相同的尺寸，而当元素从一个周期过渡到下一个周期时，原子尺寸出现了一定的增加。 [英文](#)

通过探索晶体中原子间距离之间的特定关系，可以估算出它们在化学结合中彼此连接时两者中心之间的距离。根据原子结构的刘易斯-朗缪尔理论，两种负电性的元素在结合时共用一对或若干对电子，这可以看作是一个原子的外层电子与另一个原子的外层电子在两个原子连接处重合。从这种观点出发，我们可以利用某些外壳直径的晶体数据作出估计（布拉格，《哲学杂志》，第11卷，1920年8月）。例如，氖的外壳直径就是根据碳、氮、氧和氟原子的表观直径估计得到的——估算逐渐逼近于一个最小值 1.30×10^{-8} cm。下表中的第二列给出了以上述方式得到的惰性气体的直径：

气体	直径 2σ (晶体)	直径 $2\sigma'$ (粘度)	差值 $2\sigma' - 2\sigma$
氦	—	1.89	—
氖	1.30	2.35	1.05
氩	2.05	2.87	0.82
氙	2.35	3.19	0.84
氡	2.70	3.51	0.81

第三列中给出了兰金的值（兰金，《皇家学会学报》，A辑，第98卷，第693期，第360~374页，1921年2月），这是根据查普曼公式由粘度计算出来的惰性气体的直径（查普曼，《皇家学会自然科学学报》，A辑，第216卷，第279~348页，1915年12月），它们明显大于利用晶体数据计算出的直径。但是，考虑到我们忽略了外部电子层周围的力场以及将原子连接在一起的共用电子的性质，这就不足为奇了，因为很有可能它们的结构会有一定程度的重叠。第四列显示了两种估计值之间差值的恒定性，这表明，不论结果是通过粘度还是通过晶体数据测得的，在相继加入各个电子层时，原子尺寸的增加几乎是一样的（氦的情况例外）。兰金还进一步指出， Cl_2 在粘度性质方面的表现如同两个氯原子，其中心间距与根据晶体数据计算出来的几乎相等，对于 Br_2 与氙以及 I_2 与氙来说也是如此。

英文

由此我们看到，晶体和粘度的测量结果都指出：（a）就其外部电子层的直径来说，周期表中任一周期末尾的元素几乎是一样的；（b）从一个周期过渡到下一个周期时，外部电子层尺寸会有一个确定的增加量，通过粘度估计出的这一增量的绝对数值与利用晶体数据确定的结果非常接近。

英文

HF 、 HCl 和 HBr 的红外吸收光谱可以进一步证实上述测量结果。相继的吸收谱线的波数差 $\delta\nu$ 决定了各种情况下分子的转动惯量 I ，公式为

$$\delta\nu = \frac{h}{4\pi^2 c I},$$

其中， h 为普朗克常数， c 为光速。

英文

由此就有可能计算出每个分子中核心间的距离，因为

$$s^2 = \frac{m + m'}{mm'} \cdot \frac{h}{4\pi^2 c m_{\text{H}} \delta\nu},$$

其中， m 和 m' 为相对于氢的原子量， m_{H} 为氢原子的质量。下面的表格给出了这些距离（艾姆斯，《天体物理学杂志》，第1卷，第251页，1919年）。我们将看到，从F过渡到Cl以及从Cl过渡到Br，该距离都有

所增加，并与通过晶体数据和粘度给出的电子壳层半径 σ 的增量非常接近。 [英文](#)

$s \times 10^8$			$\sigma \times 10^8$ (晶体)	$\sigma' \times 10^8$ (粘度)
HF	0.93	0.35 0.15	氟 (=F)	1.17
HCl	1.28		氯 (=Cl)	1.43
HBr	1.43		溴 (=Br)	1.58
HI	—		碘 (=I)	1.75

[英文](#)

从氟到氯的增量 $0.35 \times 10^{-8} \text{cm}$ 肯定了晶体测量给出的估计值 $0.37 \times 10^{-8} \text{cm}$ ，但与粘度数据给出的估计值 $0.26 \times 10^{-8} \text{cm}$ 不一致。根据上述结果可知，要得到氢原子核与附着其上的负电性原子中心之间的距离，只需将该原子根据晶体结构得到的半径加上 $0.26 \times 10^{-8} \text{cm}$ 即可。根据玻尔理论，内部电子轨道半径为 $0.53 \times 10^{-8} \text{cm}$ ，是这一数值的两倍。因此，晶体数据预言HI分子的 $\delta\nu = 13.0 \text{ cm}^{-1}$ ，与其原子中心间的距离 $1.61 \times 10^{-8} \text{cm}$ 相符。 [英文](#)

这个证据是引人关注的，因为它表明，将原子束缚在一起的力就位于电子层中发生连接的地方。 [英文](#)

(王耀杨 翻译；李芝芬 审稿)

Waves and Quanta

L. de Broglie

By 1923, physicists were facing up to the implications of Planck's and Einstein's discoveries about the quantized nature of light. Although a wave phenomenon, light also seemed particulate. Bohr's model of the atom had exploited the quantization principle for electrons. Here Louis de Broglie suggests that particles with mass, such as electrons, may also have associated waves, and that this idea could put Bohr's view on firmer ground. De Broglie says that Bohr's results can be obtained by demanding that an integral number of such electron waves must fit into its orbit around the nucleus. De Broglie's suggestion was confirmed in dramatic fashion by the discovery in 1927 of electron diffraction by crystals. [中文](#)

THE quantum relation, $\text{energy} = h \times \text{frequency}$, leads one to associate a periodical phenomenon with any isolated portion of matter or energy. An observer bound to the portion of matter will associate with it a frequency determined by its internal energy, namely, by its "mass at rest." An observer for whom a portion of matter is in steady motion with velocity βc , will see this frequency lower in consequence of the Lorentz-Einstein time transformation. I have been able to show (*Comptes rendus*, September 10 and 24, of the Paris Academy of Sciences) that the fixed observer will constantly see the internal periodical phenomenon in phase with a wave the frequency of which

$v = \frac{m_0 c^2}{h\sqrt{1 - \beta^2}}$ is determined by the quantum relation using the whole energy of the moving body—provided it is assumed that the wave spreads with the velocity c/β . This wave, the velocity of which is greater than c , cannot carry energy. 中文

A radiation of frequency ν has to be considered as divided into atoms of light of very small internal mass ($<10^{-50}$ gm) which move with a

velocity very nearly equal to c given by $\frac{m_0 c^2}{\sqrt{1 - \beta^2}} = h\nu$. The atom of light slides slowly upon the non-material wave the frequency of which is ν and velocity c/β , very little higher than c . 中文

The “phase wave” has a very great importance in determining the motion of any moving body, and I have been able to show that the stability conditions of the trajectories in Bohr’s atom express that the wave is tuned with the length of the closed path. 中文

The path of a luminous atom is no longer straight when this atom crosses a narrow opening; that is, diffraction. It is then *necessary* to give up the inertia principle, and we must suppose that any moving body follows always the ray of its “phase wave”; its path will then bend by passing through a sufficiently small aperture. Dynamics must undergo the same evolution that optics has undergone when undulations took the place of purely geometrical optics. Hypotheses based upon those of the wave theory allowed us to explain interferences and diffraction fringes. By means of these new ideas, it will probably be possible to reconcile also diffusion and dispersion with the discontinuity of light, and to solve almost all the problems brought up by quanta. 中文

(112, 540; 1923)

波与量子

德布罗意

物理学家们在1923年的主要工作是探讨普朗克和爱因斯坦关于光的量子性质的发现。虽然光是一种波，但它似乎也具有粒子的特性。玻尔的原子模型已经用到了电子的量子化原则。路易斯·德布罗意在本文中提出像电子这样有质量的粒子可能也有相对应的波，这一观点为玻尔的理论奠定了更坚实的基础。德布罗意认为，玻尔理论中的结果可以由电子波波长取整数以适合核外电子轨道得到。1927年，德布罗意的假设就被电子在晶体中的衍射实验成功证实了。

英文

量子关系式，即能量 = 普朗克常数 h × 频率，使人们可以把一个周期现象与任一孤立的物质或能量联系起来。与物体一起运动的观察者观测到的周期现象的频率将由物体的内部能量，即“静止质量”决定。当物体相对于观察者以 βc 的速度匀速运动时，由洛伦兹-爱因斯坦时间变换公式，观察者观测到的频率变低。我已经指出（巴黎科学院的《法国科学院院刊》，9月10日和24日），这位固定不动的观察者总能通过波的相

位看到频率为
$$\nu = \frac{m_0 c^2}{h \sqrt{1 - \beta^2}}$$
 的内禀周期性现象，该公式是依据量子关系式推导出来的，利用了运动物体的总能量，并假设波以 c/β 的速度传播。这个速度大于 c 的波不能携带能量。

英文

频率为 ν 的辐射必须被看成由内部质量极小（小于 10^{-50} 克）的光原

子组成，其运动速度（由公式
$$\frac{m_0 c^2}{\sqrt{1 - \beta^2}} = h\nu$$
 决定）很接近于 c 。这些光原子沿着频率为 ν ，速度为 c/β （仅比 c 略高一点）的非实物波缓慢行进。

英文

“相位波”对于确定任何物体的运动都是至关重要的。我已经指出，玻尔原子轨道的稳定条件表明相位波的波长应与闭合轨道的长度相匹配。 [英文](#)

当光原子穿过一个小孔时，它的路径就不再是一条直线，即产生了衍射现象。因此必须摒弃惯性原理，我们必须假定，任何运动物体总沿着它的“相位波”的放射路径行进。因此，当它经过一个足够小的孔时，其轨迹会发生弯曲。如同几何光学被波动光学取代一样，实物粒子的动力学也应经历相应的变革。我们可以利用基于波动理论的假设解释干涉和衍射产生的条纹。借助这些新思想，还有可能把漫射和散射现象与光的不连续性联系起来，解决由量子引出的几乎所有问题。 [英文](#)

（王锋 翻译；刘纯 审稿）

Thermal Agitation of Electricity in Conductors

J. B. Johnson

In the early days of electronics and telephone communications, engineers aimed to reduce the noise in their circuits to a minimum. But there are fundamental limits, as physicist and engineer John Johnson of Bell Telephone Laboratories here reports. Johnson shows that ordinary electrical conductors exhibit spontaneous, thermally induced fluctuations of voltage, even when not being driven by external currents. This voltage noise depends directly on the temperature of the sample, leading Johnson to surmise that it must arise from continual agitation and excitation by random thermal energy. Thus, he concludes, the minimum voltage that can be usefully amplified in electronic circuits is limited by the very matter from which they are built. [中文](#)

ORDINARY electric conductors are sources of spontaneous fluctuations of voltage which can be measured with sufficiently sensitive instruments. This property of conductors appears to be the result of thermal agitation of the electric charges in the material of the conductor. [中文](#)

The effect has been observed and measured for various conductors, in the form of resistance units, by means of a vacuum tube amplifier

terminated in a thermocouple. It manifests itself as a part of the phenomenon which is commonly called “tube noise”. The part of the effect originating in the resistance gives rise to a mean square voltage fluctuation V^2 which is proportional to the value R of that resistance. The ratio V^2/R is independent of the nature or shape of the conductor, being the same for resistances of metal wire, graphite, thin metallic films, films of drawing ink, and strong or weak electrolytes. It does, however, depend on temperature and is proportional to the absolute temperature of the resistance. This dependence on temperature demonstrates that the component of the noise which is proportional to R comes from the conductor and not from the vacuum tube. 中文

A similar phenomenon appears to have been observed and correctly interpreted in connexion with a *current sensitive* instrument, the string galvanometer (W. Einthoven, W. F. Einthoven, W. van der Horst, and H. Hirschfeld, *Physica*, 5, 358–360, No. 11/12, 1925). What is being measured in these cases is the effect upon the measuring device of continual shock excitation resulting from the random interchange of thermal energy and energy of electric potential or current in the conductor. Since the effect is the same for different conductors, it is evidently not dependent on the specific mechanism of conduction.

中文

The amount and character of the observed noise depend upon the frequency-characteristic of the amplifier, as would be expected from experience with the small-shot effect. The apparent input power originating in the resistance is of the order 10^{-18} watt at room temperature. The corresponding output power is proportional to the area under the graph of *power amplification–frequency*, at least in the range of audio frequencies. The magnitude of the “initial noise”, when the quietest tubes are used without input resistance, is about the same as that produced by a resistance of 5,000 ohms at room temperature in the input circuit. For the technique of amplification, therefore, the

effect means that the limit to the smallness of voltage which can be usefully amplified is often set, not by the vacuum tube, but by the very matter of which electrical circuits are built. [中文](#)

(119, 50-51; 1927)

J. B. Johnson: Bell Telephone Laboratories, Inc., New York, N. Y., Nov. 17.

导体中电的热扰动

约翰逊

在电子通讯和电话通信的早期，工程师们的目标是将电路中的噪声降至最小。但贝尔电话实验室的物理学家、工程师约翰·约翰逊认为，噪声的减少是有基本极限的。约翰逊指出：即使在没有加载外部电流的情况下，导体也会表现出由自发热扰动导致的电压波动。这种电压噪声与样品的温度直接相关，这使约翰逊联想到它应该是由随机热能的连续激励和扰动造成的。因此他得出以下结论：在电路中能够被有效放大的最小电压受到组成电路的材料限制。

英文

普通的导体是电压自发涨落的来源，而这种波动电压可以用足够灵敏的仪器进行测量。导体的这种性质是导体材料中电荷热扰动的结果。

英文

在各种导体中都已经观测到这类效应，并以电阻的形式，通过终端连接温差电偶的真空管放大器对此进行了测量。它通常作为所谓的“电子管噪声”现象的一部分而表现出来。源于电阻波动的这部分效应造成了电压均方值 V^2 的波动，此波动与电阻值 R 成正比。比率 V^2/R 与导体的性质和形状无关，对金属丝、石墨、金属薄膜、绘图墨水薄膜及强电解质或弱电解质来说，该比率都是相同的。然而，该比率却与温度有关，并与电阻的绝对温度成正比。这种温度依赖性表明，与 R 成比例的噪声分量来自导体，而不是来自真空管。

英文

目前已经有人用对电流灵敏的仪器——弦线电流计观测到类似现象并正确地进行了解释（老艾因特霍芬、小艾因特霍芬、范德霍斯特以及赫希菲尔德，《物理学》，第5卷，第358~360页，第11/12期，1925年）。在这些情况下测量到的是，导体中的热能与电势或电流能量的随

机交换引起的持续冲击激发对测量装置的影响。因为该效应对不同导体是相同的，所以显然它与传导的特定机制无关。 [英文](#)

正如从散粒效应的经验可以预期的那样，观测到的噪声的量及其特性与放大器的频率特性有关。在室温下，来自电阻的表观输入功率在 10^{-18} 瓦的量级。至少在声频范围内，相应的输出功率与功率放大-频率关系图中曲线下的面积成正比。当采用无输入电阻的最平稳的真空管时，“初始噪声”的量级约与在室温下输入回路中5,000欧姆的电阻产生的噪声量级相同。因此，对于放大技术而言，这种效应意味着可以被有效放大的电压的最小值与构成电路的材料有关，而不由真空管决定。

[英文](#)

（沈乃澍 翻译；赵见高 审稿）

The Scattering of Electrons by a Single Crystal of Nickel

C. Davisson and L. H. Germer

In his PhD thesis of 1924, Louis de Broglie hypothesized that electrons and other massive particles might behave as waves, just as photons reveal the particle-like aspects of otherwise wave-like electromagnetic radiation. This implied that material particles should exhibit wave-like phenomena such as interference or diffraction. Here Clinton Davisson and Lester Germer of the Bell Telephone Laboratories verified this prediction by measuring the diffraction of an electron beam from a nickel crystal. Using the known spacing of atomic planes in nickel, they were able to calculate the expected angles where diffracted beams should occur if the electrons were indeed acting as waves in the manner de Broglie suggested. The experimental results agreed with these predictions, and they won Davisson the 1937 Nobel Prize in physics. [中文](#)

IN a series of experiments now in progress, we are directing a narrow beam of electrons normally against a target cut from a single crystal of nickel, and are measuring the intensity of scattering (number of electrons per unit solid angle with speeds near that of the bombarding electrons) in various directions in front of the target. The experimental arrangement is such that the intensity of scattering can be measured in any latitude from the equator (plane of the target) to within 20° of

the pole (incident beam) and in any azimuth.

[中文](#)

The face of the target is cut parallel to a set of $\{111\}$ -planes of the crystal lattice, and etching by vaporisation has been employed to develop its surface into $\{111\}$ -facets. The bombardment covers an area of about 2 mm^2 and is normal to these facets.

[中文](#)

As viewed along the incident beam the arrangement of atoms in the crystal exhibits a threefold symmetry. Three $\{100\}$ -normals equally spaced in azimuth emerge from the crystal in latitude 35° , and, midway in azimuth between these, three $\{111\}$ -normals emerge in latitude 20° . It will be convenient to refer to the azimuth of any one of the $\{100\}$ -normals as a $\{100\}$ -azimuth, and to that of any one of the $\{111\}$ -normals as a $\{111\}$ -azimuth. A third set of azimuths must also be specified; this bisects the dihedral angle between adjacent $\{100\}$ - and $\{111\}$ -azimuths and includes a $\{110\}$ -normal lying in the plane of the target. There are six such azimuths, and any one of these will be referred to as a $\{110\}$ -azimuth. It follows from considerations of symmetry that if the intensity of scattering exhibits a dependence upon azimuth as we pass from a $\{100\}$ -azimuth to the next adjacent $\{111\}$ -azimuth (60°), the same dependence must be exhibited in the reverse order as we continue on through 60° to the next following $\{100\}$ -azimuth. Dependence on azimuth must be an even function of period $2\pi/3$.

[中文](#)

In general, if bombarding potential and azimuth are fixed and exploration is made in latitude, nothing very striking is observed. The intensity of scattering increases continuously and regularly from zero in the plane of the target to highest value in co-latitude 20° , the limit of observations. If bombarding potential and co-latitude are fixed and exploration is made in azimuth, a variation in the intensity of scattering of the type to be expected is always observed, but in general this variation is slight, amounting in some cases to not more than a few percent of the average intensity. This is the nature of the

scattering for bombarding potentials in the range from 15 volts to near 40 volts. 中文

At 40 volts a slight hump appears near 60° in the co-latitude curve for azimuth- $\{111\}$. This hump develops rapidly with increasing voltage into a strong spur, at the same time moving slowly upward toward the incident beam. It attains a maximum intensity in co-latitude 50° for a bombarding potential of 54 volts, then decreases in intensity, and disappears in co-latitude 45° at about 66 volts. The growth and decay of this spur are traced in Fig. 1. 中文

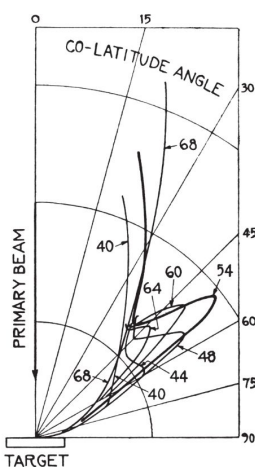


Fig. 1. Intensity of electron scattering vs. co-latitude angle for various bombarding voltages—azimuth- $\{111\}$ - 330° 中文

A section in azimuth through this spur at its maximum (Fig. 2—Azimuth- 330°) shows that it is sharp in azimuth as well as in latitude, and that it forms one of a set of three such spurs, as was to be expected. The width of these spurs both in latitude and in azimuth is almost completely accounted for by the low resolving power of the measuring device. *The spurs are due to beams of scattered electrons which are nearly if not quite as well defined as the primary beam.* The minor peaks occurring in the $\{100\}$ -azimuth are sections of a similar set of spurs that attains its maximum development in co-latitude 44° for a bombarding potential of 65 volts. 中文

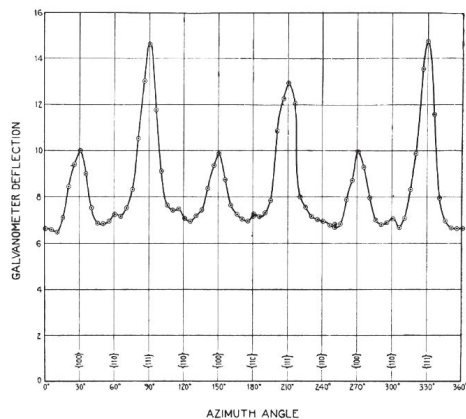


Fig. 2. Intensity of electron scattering vs. azimuth angle—54 volts, co-latitude 50° 中文

Thirteen sets of beams similar to the one just described have been discovered in an exploration in the principal azimuths covering a voltage range from 15 volts to 200 volts. The data for these are set down on the left in Table I (columns 1–4). Small corrections have been applied to the observed co-latitude angles to allow for the variation with angle of the “background scattering”, and for a small angular displacement of the normal to the facets from the incident beam. 中文

Table I

Azimuth	Electron Beams			X-ray Beams						
	Bomb. Pot (volts)	Co-lat. θ	Intensity	Reflections	$\lambda \times 10^8$ cm	Co-lat. θ	Co-lat. θ'	$v \times 10^{-8}$ cm/sec	$n\lambda \times 10^8$ cm	$n \left\{ \frac{\lambda m v}{h} \right\}$
{111}	54	50°	0.5	{220}	2.03	70.5	52.7	4.36	1.65	0.99
	100	31	0.5	{331}	1.49	44.0	31.6	5.94	1.11	0.91
	174	21	0.9	{442}	1.13	31.6	22.4	7.84	0.77	0.83
	174	55	0.15	{440}	1.01	70.5	52.7	7.84	1.76	2(0.95)
{100}	65	44	0.5	{311}	1.84	59.0	43.2	4.79	1.49	0.98
	126	29	1.0	{422}	1.35	38.9	27.8	6.67	1.04	0.95
	190	20	1.0	{533}	1.04	28.8	20.4	8.19	0.74	0.83
	159	61	0.4	{511}	1.05	77.9	59.0	7.49	1.88	2(0.97)
{110}	138	59	0.07	{420}	1.22	78.5	59.5	6.98	1.06	1.02
	170	46	0.07	{531}	1.04	57.1	41.7	7.75	0.89	0.95
{111}	110	58	0.15	..	..	..	..	6.23	1.82	1.56
{100}	110	58	0.15	..	..	..	..	6.23	1.82	1.56
{110}	110	58	0.25	..	..	..	..	6.23	1.05	0.90

If the incident electron beam were replaced by a beam of monochromatic X-rays of adjustable wave-length, very similar phenomena would, of course, be observed. At particular values of wave-length, sets of three or of six diffraction beams would emerge from the incident side of the target. On the right in Table I (columns 5, 6 and 7) are set down data for the ten sets of X-ray beams of longest wave-length which would occur within the angular range of our observations. Each of these first ten occurs in one of our three principal azimuths. 中文

Several points of correlation will be noted between the two sets of data. Two points of difference will also be noted; the co-latitude angles of the electron beams are not those of the X-ray beams, and the three electron beams listed at the end of the Table appear to have no X-ray analogues. 中文

The first of these differences is systematic and may be summarised quantitatively in a simple manner. If the crystal were contracted in the direction of the incident beam by a factor 0.7, the X-ray beams would be shifted to the smaller co-latitude angles θ' (column 8), and would then agree in position fairly well with the observed electron beams—the average difference being 1.7° . Associated in this way there is a set of electron beams for each of the first ten sets of X-ray beams occurring in the range of observations, the electron beams for 110 volts alone being unaccounted for. 中文

These results are highly suggestive, of course, of the ideas underlying the theory of wave mechanics, and we naturally inquire if the wave-length of the X-ray beam which we thus associate with a beam of electrons is in fact the h/mv of L. de Broglie. The comparison may be made, as it happens, without assuming a particular correspondence between X-ray and electron beams, and without use of the contraction

factor. Quite independently of this factor, the wave-lengths of all possible X-ray beams satisfy the optical grating formula $n\lambda = d\sin\theta$, where d is the distance between lines or rows of atoms in the surface of the crystal—these lines being normal to the azimuth plane of the beam considered. For azimuths-{111} and-{100}, $d = 2.15 \times 10^{-8}$ cm and for azimuth-{110}, $d = 1.24 \times 10^{-8}$ cm. We apply this formula to the electron beams without regard to the conditions which determine their distribution in co-latitude angle. The correlation obtained by this procedure between wave-length and electron speed v is set down in the last three columns of Table I. 中文

In considering the computed values of $n(\lambda mv/h)$, listed in the last column, we should perhaps disregard those for the 110-volt beams at the bottom of the Table, as we have had reason already to regard these beams as in some way anomalous. The values for the other beams do, indeed, show a strong bias toward small integers, quite in agreement with the type of phenomenon suggested by the theory of wave mechanics. These integers, one and two, occur just as predicted upon the basis of the correlation between electron beams and X-ray beams obtained by use of the contraction factor. The systematic character of the departures from integers may be significant. We believe, however, that this results from imperfect alignment of the incident beam, or from other structural deficiencies in the apparatus. The greatest departures are for beams lying near the limit of our co-latitude range. The data for these are the least trustworthy. 中文

(119, 558-560; 1927)

镍单晶对电子的散射

戴维森，革末

1924年，路易斯·德布罗意在博士论文中猜测，电子以及其他一些有质量的粒子的运动方式可能与波类似，就像光子除了具有电磁辐射的波动行为以外，还显示出与此不同的粒子行为。这一假说意味着，物质粒子会表现出干涉或者衍射这样的波动特征。在这篇文章中，贝尔电话实验室的克林顿·戴维森和莱斯特·革末通过对从镍晶中发出的电子束的衍射效应进行测量证实了这一假说。如果正如德布罗意猜想的那样电子具有像波一样的性质，那么根据镍晶中已知的原子平面之间的间距，他们就能计算出应该出现衍射束的预期角度。实验结果与这些预测是相吻合的。戴维森因此获得了1937年的诺贝尔物理学奖。 [英文](#)

现在正在进行的一系列实验中，我们用一窄束电子垂直轰击一块从镍单晶上切下来的靶子，并测量了靶前方不同方向上的电子散射强度（与每单位立体角中速度和轰击电子的速度相似的电子数量）。我们的实验装置可以测量从赤道（靶平面）到与轴（入射束）成 20° 范围内在任意纬度处和在任意方位角上的散射强度。 [英文](#)

被切割下来的靶面平行于镍单晶点阵的一组 $\{111\}$ 面，切下来之后用蒸气进行蚀刻，以使其表面形成一系列 $\{111\}$ 小晶面。轰击的电子束打在约2平方毫米的范围内，并与以上的小晶面垂直。 [英文](#)

沿着入射电子束的方向观察，我们发现原子在晶体中的排列呈现三重对称。从晶体出发，在纬度为 35° 处有三条相隔同样方位角的 $\{100\}$ 法线，并且在这些方位角中间，有三条 $\{111\}$ 法线出现在纬度 20° 处。为了方便起见，任何一条 $\{100\}$ 法线的方位角都可以被看作是一个 $\{100\}$ 方位角，任何一条 $\{111\}$ 法线的方位角也可以被看作是一个 $\{111\}$ 方位角。我

们还必须指定第三组方位角；它将平分相邻的{100}方位角和{111}方位角之间的二面角，并且包含一条位于靶平面上的{110}法线。有6个这样的方位角，它们当中的任意一个都可以被看作是一个{110}方位角。考虑到对称性的要求，当从{100}方位角转到下一个相邻的{111}方位角（60°）时，如果散射强度的变化依赖于方位角的话，那么当从60°转到下一个相邻的{100}方位角时，相同的依赖关系会按相反的次序再现。散射强度对方位角的依赖关系肯定是一个周期为 $2\pi/3$ 的偶函数。

英文

一般来说，如果轰击电压和方位角固定，当沿着纬度测量的时候，不会观察到任何令人惊奇的现象。散射强度连续而有规律地从靶平面处的零增加到余纬20°时的最大值，余纬20°是我们的观测极限。如果轰击电压和余纬固定，而沿着方位角进行探测，则通常可以观察到预期之中的散射强度变化，但总的来说这种差别很小，在某些情况下总的变化量不会大于平均强度的百分之几。这就是散射在轰击电压从15伏特到接近40伏特之间变动时的特性。

英文

当电压为40伏特时，在方位角为{111}的余纬曲线上接近60°处出现了一个小峰。随着电压的增加，这个峰迅速变大形成一个很强的尖峰，同时朝着入射电子束的方向缓慢向上提升。当轰击电压为54伏特，余纬为50°时，峰值达到最大，然后强度逐渐减小，在电压约为66伏特，余纬为45°时消失。图1描述了这个尖峰从增大到衰减的过程。

英文

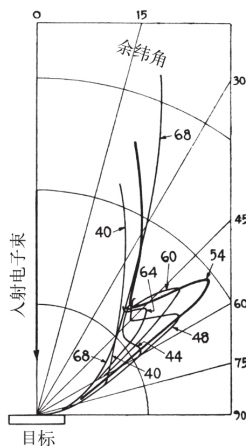


图1．不同轰击电压下电子散射强度随余纬角的变化——方位角{111}-330°

英文

在最大值处穿过这个尖峰的方位角截面图（图2之方位角330°）表明，它以方位角为变量的时候和以纬度为变量的时候一样尖锐，并且，如我们所料，它形成了3个尖峰组合中的一个。这些尖峰的宽度在随方位角变化和随纬度变化时都较大，几乎可以肯定地说这是由测量仪器的低分辨率造成的。尖峰是由散射的电子束引起的，对这些散射电子束的界定即使不能像对原射线束的界定那样精确，至少也能相差不多。在{100}方位角上出现的次级峰是另一组类似的尖峰，它们在余纬44°，轰击电压65伏特时达到最大值。

英文

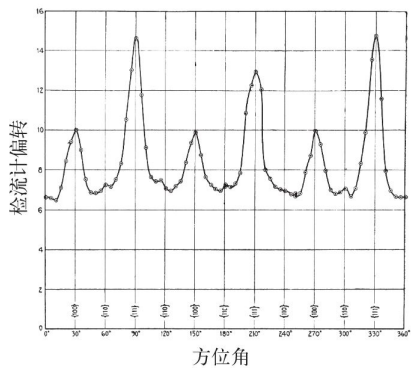


图2．电子散射强度随方位角的变化——54伏特，余纬50°

英文

电压在从15~200伏特的范围内变动时，我们在主方位角方向发现了13组与上面所描述的电子束类似的射束。结果见表I左侧（第1~4列）。考虑到“背景散射”随角度的变化，以及晶面法线与入射电子束之间的角位移，我们对观察到的余纬角进行了微小的修正。

英文

表I

方位角	电子束			X 射线束						
	轰击电压 (伏特)	余纬度 θ	强度	反射	$\lambda \times 10^8$ 厘米	余纬度 θ	余纬度 θ'	$v \times 10^{-8}$ 厘米/秒	$n\lambda \times 10^8$ 厘米	$n \left\{ \frac{\lambda m v}{h} \right\}$
{111}	54	50°	0.5	{220}	2.03	70.5	52.7	4.36	1.65	0.99
	100	31	0.5	{331}	1.49	44.0	31.6	5.94	1.11	0.91
	174	21	0.9	{442}	1.13	31.6	22.4	7.84	0.77	0.83
	174	55	0.15	{440}	1.01	70.5	52.7	7.84	1.76	2(0.95)
{100}	65	44	0.5	{311}	1.84	59.0	43.2	4.79	1.49	0.98
	126	29	1.0	{422}	1.35	38.9	27.8	6.67	1.04	0.95
	90	20	1.0	{533}	1.04	28.8	20.4	8.19	0.74	0.83
	159	61	0.4	{511}	1.05	77.9	59.0	7.49	1.88	2(0.97)
{110}	138	59	0.07	{420}	1.22	78.5	59.5	6.98	1.06	1.02
	170	46	0.07	{531}	1.04	57.1	41.7	7.75	0.89	0.95
{111}	110	58	0.15	..	..	..	..	6.23	1.82	1.56
{100}	110	58	0.15	..	..	..	..	6.23	1.82	1.56
{110}	110	58	0.25	..	..	..	..	6.23	1.05	0.90

英文

如果入射电子束被一束波长可调的单色X射线取代，我们当然可以观察到非常类似的现象。当波长为一些特定值时，在靶的入射面一侧就会出现3条一组或6条一组的衍射光束。表I右侧（第5、6、7列）列出了在我们能观测到的角度范围内由波长最长的10组X射线束得到的数据。前10组中每组数据都来自我们先前设定的3个主方位角中的一个。

英文

在以上表中关于电子束和X射线束的两部分数据中有几点关系值得我们注意。同时还要注意两个区别：电子束的余纬角不是X射线束的余纬角；对于表格底部列出的3行电子束数据，没有X射线束数据与之对应。

英文

第一个区别是系统上的，可以用一种简单的方式定量地总结出来。如果晶体沿着入射束方向被压缩至70%，即压缩因子为0.7，那么X射线束将移至更小的余纬角 θ' （第8列），这样它的位置将与观测到的电子束的情况精确地吻合——平均差异为1.7°。同理，对于我们能观察到的前10组X射线束中的每一个，都存在一组电子束与之对应，只有110伏特的电子束不能应用这种方法。

英文

当然，这些结果完全证实了波动力学理论的基本观点，我们自然很想知道，与电子束相关联的X射线束的波长是否就是德布罗意所说的 h/v

mv 。也许不用假设X射线束和电子束之间的特定关系，也不用使用压缩因子，我们就可以作出比较。所有的X射线束都满足光栅公式 $n\lambda = d\sin\theta$ ，这与压缩因子完全不相干，在这个公式中， d 是位于晶体表面的原子行或列的间距——这些行列都垂直于我们粒子束所在的方位角平面。对于方位角 $\{111\}$ 和方位角 $\{100\}$ ， $d = 2.15 \times 10^{-8}$ 厘米；对于方位角 $\{110\}$ ， $d = 1.24 \times 10^{-8}$ 厘米。我们可以把这个公式应用于电子束中而无需考虑支配电子束沿余纬度分布情况的因素。用这种方式得到的波长和电子速度 v 之间的关系列于表I的最后3列中。 [英文](#)

至于在最后一列中列出的计算值 $n(\lambda mv/h)$ ，我们可能应该不考虑表格底部110伏特的电子束数据，因为我们已经有理由把这些电子束看作是异常情况。对于其他电子束， $n(\lambda mv/h)$ 值趋向于一个比较小的整数，与波动力学理论预言的现象十分吻合。使用压缩因子对电子束和X射线束之间的差别进行校正之后，也得到了预想的结果，即整数1和2。对整数的偏离可能主要是由系统特性造成的。我们认为误差来自入射束不严格准直或者仪器的其他结构缺陷。最大的偏离出现在我们能观察到的余纬度极限附近，那里的数据是最不可靠的。 [英文](#)

(王静 翻译；赵见高 审稿)

The Continuous Spectrum of β -rays

C. D. Ellis and W. A. Wooster

Since the discovery of radioactivity in 1895, three different mechanisms had been identified. In some cases an atom would disintegrate by shedding an α -particle (the nucleus of a helium atom), in others by emitting a γ -ray (a high-frequency X-ray). In both these mechanisms, the amount of energy lost in the disintegration was found to be the same for each kind of disintegrating atom. In the third mechanism of radioactive decay, however, in which the particle shed during the disintegration is an electron, the energy carried away by the particle is indeterminate, ranging from zero to a certain maximum characteristic of the atom concerned. This raises problems referred to in the letter below. [中文](#)

THE continuous spectrum of the β -rays arising from radio-active bodies is a matter of great importance in the study of their disintegration. Two opposite views have been held about the origin of this continuous spectrum. It has been suggested that, as in the α -ray case, the nucleus, at each disintegration, emits an electron having a fixed characteristic energy, and that this process is identical for different atoms of the same body. The continuous spectrum given by these disintegration electrons is then explained as being due to secondary effects, into the nature of which we need not enter here. The alternative theory supposes that the process of emission of the

electron is not the same for different atoms, and that the continuous spectrum is a fundamental characteristic of the type of atom disintegrating. Discussion of these views has hitherto been concerned with the problem of whether or not certain specified secondary effects could produce the observed heterogeneity, and although no satisfactory explanation has yet been given by the assumption of secondary effects, it was most important to clear up the problem by a direct method.

中文

There is a ready means of distinguishing between the two views, since in one case a given quantity of energy would be emitted at each disintegration equal to or greater than the maximum energy observed in the electrons escaping from the atom, whereas in the second case the average energy per disintegration would be expected to equal the average energy of the particles emitted. If we were to measure the total energy given out by a known amount of material, as, for example, by enclosing it in a thick-walled calorimeter, then in the first case the heating effect should lead to an average energy per disintegration equal to or greater than the fastest electron emitted, no matter in what way this energy was afterwards split up by secondary effects. Since on the second hypothesis no secondary effects are presumed to be present, the heating effect should correspond simply to the average kinetic energy of the particles forming the continuous spectrum.

中文

To avoid complications due to α -rays or to γ -rays from parent or successive atoms, we measured the heating effect in a thick-walled calorimeter of a known quantity of radium E. This measurement proved difficult because of the small rate of evolution of heat, but by taking special precautions it has been possible to show that the average energy emitted at each disintegration of radium E is $340,000 \pm 30,000$ volts. This result is a striking confirmation of the hypothesis that the continuous spectrum is emitted as such from the nucleus,

since the average energy of the particles as determined by ionisation measurements over the whole spectrum gives a value about 390,000 volts, whereas if the energy emitted per disintegration were equal to that of the fastest β -rays, the corresponding value of the heating would be three times as large—in fact, 1,050,000 volts. [中文](#)

Many interesting points are raised by the question of how a nucleus, otherwise quantised, can emit electrons with velocities varying over a wide range, but consideration of these will be deferred until the publication of the full results. [中文](#)

(119, 563-564; 1927)

C. D. Ellis, W. A. Wooster: Cavendish Laboratory, Cambridge, Mar.23.

β 射线的连续谱

埃里斯，伍斯特

自从1895年发现放射性以来，人们已经确认放射性存在三种不同的机制。在某些情况下，原子会通过放射出一个 α 粒子（氦原子的原子核）而衰变，而在另一些情况下，原子会通过放射 γ 射线（一种高频X射线）而衰变。在这两种机制中，每一种衰变原子在衰变过程中的能量损失都是相同的。然而在放射性衰变的第三种机制中，原子衰变时放射出的粒子是电子，这个电子携带的能量是不确定的，其范围是从零到相关原子的最大特征能量。这就引发了下文提到的问题。 [英文](#)

在物质衰变的研究中，放射性物质产生的 β 射线连续谱是一个非常重要的问题。关于这种连续谱的起源有两种相反的观点。一种观点认为，和放射出 α 射线的衰变一样，在每一次衰变中原子核都发射出一个具有固定的特征能量的电子，并且对同一物体的不同原子这个过程都是相同的。于是，这些衰变电子的连续谱就被归因为二次效应，而有关二次效应的本质我们不必在这里进行讨论。另外一种观点认为，发射电子的过程对不同原子是不同的，并且连续谱是衰变原子类型的基本特征。关于这两种观点的讨论至今停留在是否有某种具体的二次效应能够产生可观测的连续谱这一问题上，尽管二次效应的假设还没能给出一个令人满意的解释，但最重要的是，我们应该用一种直接的方法来解释以上的问题。 [英文](#)

有一个简易的方法可以区分以上两种观点，因为从第一个观点来看，每次衰变中放出的特定能量应该等于或者大于观察到的从原子中逃逸出的电子的最大能量，而从第二种观点来看，每次衰变的平均能量应该等于发射的电子的平均能量。如果我们测量一定量的物质发射出的电

子的总能量，例如将这些物质放在一个厚壁量热计中，那么按照第一种观点，由热效应就能得出每次衰变的平均能量，这个值应该是等于或大于发射出的最快的电子的能量，不管这个能量随后以什么方式被二次效应分解。而在第二种观点中，由于不存在二次效应，所以热效应应该简单地对应于形成连续谱的电子的平均动能。 [英文](#)

为了避免衰变中母原子或后续原子产生的 α 射线或者 γ 射线的干扰，我们在厚壁量热计中测量了一定量的镭E的热效应。由于放热速度很慢，这个测量很难进行，但是通过采用特别的措施，我们得到镭E每次衰变辐射出的平均能量是 $340,000 \pm 30,000$ 电子伏。这个结果对于连续谱来源于原子核中的发射这一假设是个有力的确证。因为通过电离测量整个能谱而得到的电子平均能量大约是390,000电子伏，如果每次衰变放出的能量等于最快的 β 射线的能量，那么相应的热效应的值就应该是当前测量值的3倍，即1,050,000电子伏。 [英文](#)

一个量子化的原子核怎么能发射速度变化范围如此广泛的电子？这个问题引发了很多有趣的观点，不过还是等到详细的结果发表之后再考虑这些。 [英文](#)

（王锋 翻译；江丕栋 审稿）

A New Type of Secondary Radiation

C. V. Raman and K. S. Krishnan

Physics in the early twentieth century was dominated by scientists in Europe and the United States. Yet a landmark discovery in quantum physics is reported here by two Indian physicists in Calcutta. As hitherto understood, light scattering from a stationary material object should preserve its frequency. But Chandrasekhara Venkata Raman and Kariamanickam Srinivasa Krishnan demonstrate that a small part of the scattered light can significantly change frequency. This “Raman effect” involves an exchange of energy between the scattered photons and the internal degrees of freedom of atoms or molecules. The effect is used today to probe molecular structure and motion, and the chemical nature of materials. For his discovery, Raman was awarded the 1930 Nobel Prize in physics. [中文](#)

IF we assume that the X-ray scattering of the “unmodified” type observed by Prof. Compton corresponds to the normal or average state of the atoms and molecules, while the “modified” scattering of altered wave-length corresponds to their fluctuations from that state, it would follow that we should expect also in the case of ordinary light two types of scattering, one determined by the normal optical properties of the atoms or molecules, and another representing the effect of their fluctuations from their normal state. It accordingly becomes necessary

to test whether this is actually the case. The experiments we have made have confirmed this anticipation, and shown that in every case in which light is scattered by the molecules in dust-free liquids or gases, the diffuse radiation of the ordinary kind, having the same wave-length as the incident beam, is accompanied by a modified scattered radiation of degraded frequency. 中文

The new type of light scattering discovered by us naturally requires very powerful illumination for its observation. In our experiments, a beam of sunlight was converged successively by a telescope objective of 18 cm aperture and 230 cm focal length, and by a second lens of 5 cm focal length. At the focus of the second lens was placed the scattering material, which is either a liquid (carefully purified by repeated distillation *in vacuo*) or its dust-free vapour. To detect the presence of a modified scattered radiation, the method of complementary light-filters was used. A blue-violet filter, when coupled with a yellow-green filter and placed in the incident light, completely extinguished the track of the light through the liquid or vapour. The reappearance of the track when the yellow filter is transferred to a place between it and the observer's eye is proof of the existence of a modified scattered radiation. Spectroscopic confirmation is also available. 中文

Some sixty different common liquids have been examined in this way, and every one of them showed the effect in greater or less degree. That the effect is a true scattering and not a fluorescence is indicated in the first place by its feebleness in comparison with the ordinary scattering, and secondly by its polarisation, which is in many cases quite strong and comparable with the polarisation of the ordinary scattering. The investigation is naturally much more difficult in the case of gases and vapours, owing to the excessive feebleness of the effect. Nevertheless, when the vapour is of sufficient density, for example with ether or amylene, the modified scattering is readily

demonstrable. [中文](#)

(121, 501-502; 1928)

C. V. Raman, K. S. Krishnan: 210 Bowbazar Street, Calcutta, India, Feb. 16.

一种新型的二次辐射

拉曼，克里希南

20世纪早期的物理学主要是由欧美科学家主导的，然而，一项在量子物理方面具有里程碑意义的发现却是由两名印度物理学家在加尔各答作出的。就当时人们所知，从一个静止实物散射出来的光线应该保持频率不变，这一点大家都可以理解，但钱德拉塞卡拉·文卡塔·拉曼和卡瑞马尼卡姆·斯里尼瓦桑·克里希南却用实验证实，有一小部分散射光频率变化很大。“拉曼效应”包含散射光子与原子或分子的内自由度之间能量的交换过程。现在利用这个效应可以检测分子结构和分子运动以及材料的化学性质。拉曼因发现了这个效应而获得了1930年的诺贝尔物理学奖。 [英文](#)

如果我们假定，康普顿教授观察到的“不变”的X射线散射对应于原子和分子的正常态或平均态，而波长发生改变的“变”散射对应于原子和分子相对于正常态或平均态的涨落，那么我们就可以预测，普通光的散射应该也存在两种类型，一种取决于原子或分子的正常光学性质，另一种则代表了它们相对于正常态的涨落效应。因此有必要检验真实的情况是否确实如此。我们的实验证实了上述预测。实验表明，由任何一种无尘的液体或气体分子造成的光散射，都不仅包含了与入射光波长相同的正常漫射辐射，同时也伴随频率发生变化的变散射辐射。 [英文](#)

要观察到我们发现的这种新型光散射，自然就需要非常强的光照。在我们的实验中，一束太阳光依次通过口径为18厘米、焦距为230厘米的望远镜物镜和一个焦距为5厘米的透镜而被会聚。在第二个透镜的焦点处放置散射材料，这些材料或者是在真空中反复蒸馏得到的非常纯净的液体，或者是无尘的蒸气。为了探测变散射辐射的存在，我们使用了互补的滤光片。当把一个蓝紫色滤光片和一个黄绿色滤光片一起放置在

入射光处时，透过液体或蒸气的光路会完全消失。而当把入射光处的黄色滤光片移置到散射材料和观测者的眼睛之间时，透过散射材料的光路就会重新出现。这就证实了变散射辐射的存在。光谱分析的结果也证实了这一点。 [英文](#)

我们用这种方法检测了六十多种不同的常见液体，所有结果中都或多或少地出现了这种效应。这是一种真正的散射效应而不是一种荧光现象，因为与普通的散射相比它的强度非常微弱，而且在很多情况下它具有与普通的散射相当的非常强的偏振性。这种效应的强度非常微弱，因此要在气体和蒸气中开展这项研究自然是非常困难的。不过，当蒸气浓度足够大时，例如乙醚或戊烯的蒸气，还是很容易观察到变散射的。

[英文](#)

（王锋 翻译；李芝芬 审稿）

Wave Mechanics and Radioactive Disintegration

R. W. Gurney and E. U. Condon

The “wave mechanics” description of quantum theory arose from the work of Erwin Schrödinger in the 1920s, which built on the suggestion of Louis de Broglie in 1924 that matter can possess wave-like properties. Schrödinger’s description of the behaviour of quantum particles was formulated purely in terms of waves (or wavefunctions) whose amplitude in different parts of space specified the probability of the particle being there. Here Ronald Gurney and Edward Condon perceptively states what this implies for the decay of radioactive atomic nuclei by emission of alpha particles. They points out that the escape of the alpha particle can be regarded simply in terms of overlap between wavefunctions inside and outside the nucleus. This is a form of quantum “tunnelling” through an energy barrier. [中文](#)

AFTER the exponential law in radioactive decay had been discovered in 1902, it soon became clear that the time of disintegration of an atom was independent of the previous history of the atom and depended solely on chance. Since a nuclear particle must be held in the nucleus by an attractive field, we must, in order to explain its ejection, arrange for a spontaneous change from an attractive to a repulsive field. It has hitherto been necessary to postulate some special arbitrary “instability” of the nucleus; but in the following note

it is pointed out that disintegration is a natural consequence of the laws of quantum mechanics without any special hypothesis. 中文

It is well known that the failure of classical mechanics in molecular events is due to the fact that the wave-length associated with the particles is not small compared with molecular dimensions. The wave-length associated with α -particles is some 10^5 smaller, but since the nuclear dimensions are smaller than atomic in about the same ratio, the applicability of the wave mechanics would seem to be ensured.

中文

In the classical mechanics, the orbit of a moving particle is entirely confined to those parts of space for which its potential energy is less than its total energy. If a ball be moving in a valley of potential energy and have not enough energy to get over a mountain on one side of the valley, it must certainly stay in the valley for all time, unless it acquire the deficiency in energy somehow. But this is not so on the quantum mechanics. It will always have a small but finite chance of slipping through the mountain and escaping from the valley. 中文

In the diagram (Fig.1), let O represent the centre of a nucleus, and let $ABCDEFGF$ represent a simplified one-dimensional plot of the potential energy. The parts ABC and GHK represent the Coulomb field of repulsion outside the nucleus, and the internal part $CDEFG$ represents the attractive field which holds α -particles in their orbits. Let DF be an allowed orbit the energy of which, say 4 million volts, is given by the height of DF above OX . Approximately, we can say that with this orbit will be associated a wave-function which will die away exponentially from D to B . Again, corresponding to motion outside the nucleus along BM , there will be a wave-function which will die away exponentially from B to D . The fact that these two functions overlap in the region BD means that there is a small but finite probability that the particle in the orbit DF will escape from the nucleus along BM , acquiring kinetic

energy equal to the height of *DFBM* above *OX*, say 4 million volts. This occurrence will be spontaneous and governed solely by chance.

中文

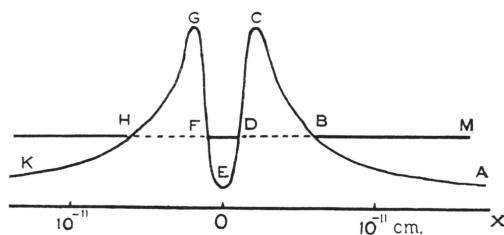


Fig. 1 中文

The rate of disintegration, that is, the probability of escape, depends on the amount of overlapping of the wave-functions in the regions *DB* and *FH*, and this is extremely sensitive to the height to which the potential curve at *C* rises above *BDF*. By varying this height through a small range we can obtain all periods of radioactive decay from a fraction of a second, through the 10^9 years of uranium, to practical stability. (In considering the transmutation of a molecule into its isomer, Hund found a similar vast range of transformation periods, *Zeit. f. P.*, 43, 810; 1927) If the potential curves for the interaction of an α -particle with the various radioactive nuclei are similar, we can obtain a qualitative understanding of the Geiger-Nuttall relation between the rate of disintegration and the range of the emitted α -particles. For the α -particles of high energy the wave function for outside motion will overlap that for the inside motion more, and the rate of disintegration will be greater. 中文

Besides obtaining a general idea of the mysterious instability of the nucleus, we can visualise in this way one of the most puzzling results of recent experimental work. An α -particle having the same range (2.7 cm) as those emitted by uranium should, if fired directly at the uranium nucleus, penetrate its structure; while faster α -particles should do so, even when not fired directly at the nucleus. It was therefore disconcerting when, on examining the scattering of fast α -

particles fired at uranium, Rutherford and Chadwick (*Phil. Mag.*, 50, 904; 1925) could find no indication of any departure from the inverse square laws. But from the model outlined above, this is what would be expected. For if the height of BM above OX represents the energy of the uranium α -particles, then a faster particle fired at the nucleus will simply run part way up the hill ABC and return without having encountered any change in the repulsive field or any nuclear particles (which are describing orbits within the region GEC). 中文

The peculiar property of the wave mechanical equations which finds application here has also been applied to the theory of the emission of electrons from cold metals under the action of intense fields (Oppenheimer, *Proc. Nat. Acad. Sci.*, 14, 363; 1928; and Fowler and Nordheim, *Proc. Roy. Soc.*, A, 119, 173; 1928). Ordinarily, an atom does not lose its electrons because the attractive field of the atom remains attractive to all distances. But when an intense field is applied, then the attractive field is reversed in sign a short distance from the atom. This makes the resultant potential energy curve similar to that in the diagram, and so the atoms begin to shed their electrons.

中文

Much has been written of the explosive violence with which the α -particle is hurled from its place in the nucleus. But from the process pictured above, one would rather say that the α -particle slips away almost unnoticed. 中文

(122, 439; 1928)

Ronald W. Gurney, Edw. U. Condon: Palmer Physical Laboratory, Princeton University, July 30.

波动力学和放射性衰变

格尼，康登

20世纪20年代，埃尔温·薛定谔在路易斯·德布罗意于1924年提出的物质可能具有波动性这个观点的基础上进行了一系列研究工作，开启了用“波动力学”描述量子理论的先河。薛定谔完全从波（或者说是波函数）的角度系统地描述了量子化粒子的行为，空间中不同位置上波的振幅代表了粒子在该处出现的概率。在这篇文章中，罗纳·德·格尼和爱德华·康登敏锐地指出了薛定谔的描述对于理解放射性原子核发射出 α 粒子的衰变的意义。他们认为， α 粒子的逃逸可以简单地理解成核内外波函数的重叠。这正是一种穿透能量壁垒的量子“隧道效应”。 [英文](#)

在1902年放射性衰变的指数律被发现后，人们很快认识到一个原子衰变的时间与这个原子以前的历史无关，而完全是由概率决定的。因为核子一定是被引力场束缚在原子核中的，所以为了解释核子的发射，我们必须假设一个从引力场到斥力场的自发转变。目前，有必要假设原子核具有某种特别的任意“不稳定性”，但在下文中，我们会指出衰变是量子力学原理的固有结果，并不需要任何特别的假设。 [英文](#)

众所周知，经典力学在分子事件中失效是由于与分子尺度相比粒子的波长较大。 α 粒子的波长约为分子尺度的 $1/10^5$ ，但因为原子核的尺度比原子尺度小差不多同样的比率，波动力学的适用性似乎是有保证的。

[英文](#)

在经典力学中，一个运动粒子的轨道被严格限制在势能小于总能量的区域内。如果一个球在势阱中运动，并且其能量不足以使它翻过势垒，那么它将一直呆在势阱中，除非它以某种方式获得足以翻越势垒的能量。但在量子力学中情况并非如此，球总是有一个很小但不为零的机

会可以穿透势垒从势阱中逃逸出来。 英文

如图1所示，设O表示一个原子核的中心，*ABCDEFGG*表示一条简化了的一维势能曲线。其中，*ABC*段和*GHK*段表示核外的库仑排斥场；中间的*CDEFG*段表示将 α 粒子束缚在其轨道上的引力场。设*DF*是一个容许轨道，它的能量，比如说400万电子伏，由OX到*DF*的高度表示。我们可以近似地说，这个轨道对应的波函数从*D*到*B*呈指数衰减。此外，相应于核外运动的*BM*段中，粒子运动的波函数从*B*到*D*也呈指数衰减。这两个波函数在*BD*区域交叠的事实意味着，存在一个很小但不为零的概率，使得在*DF*轨道上的粒子能够沿着*BM*逃逸出原子核，同时获得OX到*DFBM*的高度所表示的动能，比如说400万电子伏。这一事件是自发的并且只受概率控制。 英文

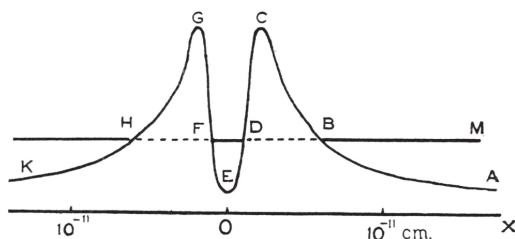


图1 英文

衰变速率，即逃逸概率，依赖于*DB*和*FH*区域中波函数的交叠量，并且对势能曲线中*C*点到*BDF*的高度十分敏感。通过在小范围内改变这个高度，我们可以获得所有放射性衰变元素的衰变周期，从几分之一秒、 10^9 年（铀）到实质上是稳定的，各种情况都存在。（在考察分子的异构体之间的转化时，洪德发现了一个与此类似的转变周期的巨大范围，见《物理学杂志》，第43卷，第810页，1927年）如果 α 粒子与各种放射性核相互作用的势能曲线是类似的，我们就能定性地理解衰变速率和所发射 α 粒子的射程之间的盖革-努塔耳关系。对于高能 α 粒子，核外运动波函数与核内运动波函数交叠得更多，从而衰变速率将会更大。

英文

除了获得关于原子核神秘不稳定性的一般观点以外，以此方法我们还可以解释最近实验工作中最令人迷惑的一些结果中的一个。如果一个与铀发射出的 α 粒子射程相同（2.7厘米）的 α 粒子直接射在铀核上，它

将穿透铀核；而更快的 α 粒子即使不是直接射在铀核上，也会穿透铀核。因此，令人不解的是，在快 α 粒子射在铀上的散射实验中，卢瑟福和查德威克（《哲学杂志》，第50卷，第904页，1925年）没能发现任何偏离库仑平方反比定律的迹象。但是从以上概述的模型来看，这应该是预期的结果。因为如果OX到BM的高度表示铀发射的 α 粒子的能量，那么射在核上的更快的粒子将仅仅沿着势垒ABC向上爬一段然后返回，其间没有经历排斥场的任何变化也没有遇到任何核子（核子在GEC区域内运动）。 [英文](#)

这里应用到的波动力学方程的特殊性质也曾被应用于强场作用下冷金属发射电子的理论中（奥本海默，《美国科学院院刊》，第14卷，第363页，1928年；福勒和诺德海姆，《皇家学会学报》，A辑，第119卷，第173页，1928年）。一般情况下，原子不会失去它的电子，因为不论相隔多远的距离，原子的引力场都吸引着电子。然而，当施加一个强场时，原子附近一个短距离范围之内，原子引力场将被颠倒。这使得合成的势能曲线类似于图1中的曲线，因此原子开始发射它们的电子。

[英文](#)

很多文献都提到了将 α 粒子从原子核内抛出的一种爆炸性的力量。然而，从以上描绘的过程来看，人们宁愿说 α 粒子几乎是神不知鬼不觉地溜出原子核的。 [英文](#)

（王锋 翻译；李军刚 审稿）

The “Wave Band” Theory of Wireless Transmission

A. Fleming

Ambrose Fleming here takes issue with a way of understanding wave communications, for telephone or television. In both technologies, devices encode signals as amplitude modulations of a carrier wave. In terms of Fourier analysis, one can view the resulting wave as occupying a “band” of frequencies around the carrier frequency, and it had become common to consider how these bands should be apportioned, which bands were allowed and so forth. But Fleming argues that talk of bands obscures the role of the amplitude. Too large an amplitude could cause interference between different transmissions, much as speaking too loudly at the theatre can be disruptive. Focusing on amplitude rather than bands, Fleming suggests, will help avoid unnecessary restrictions on the new technologies.

[中文](#)

IN scientific history we meet with many examples of scientific theories or explanations which have been widely adopted and employed, not because they can be proved to be true but because they provide a simple, easily grasped, plausible explanation of certain scientific phenomena. The majority of persons are not able to see their way through complicated phenomena and so thankfully adopt any short-cut to a supposed comprehension of them without objection.

Ease of comprehension is not, however, a primary quality of Nature, and it does not follow that because we can imagine a mechanism capable of explaining some natural phenomenon it is therefore accomplished in that way. There is a widely diffused belief in a certain theory of wireless telephonic transmission, and also of television, that for securing good effects it is necessary to restrict or include operations within a certain width of "wave band". But although this view has been very much adopted there is good reason to think that it is merely a kind of mathematical fiction and does not correspond to any reality in Nature. 中文

Let us consider how it has arisen. We send out from all wireless telephone transmitters an electromagnetic radiation of a certain definite and constant frequency expressed in kilocycles. Thus 2LO London broadcasts on 842 kilocycles. This means that it sends out 842,000 electric vibrations or waves per second. Every broadcasting station has allotted to it a certain frequency of oscillation and it is not allowed to depart from it. 中文

It is like a lighthouse which sends out rays of light of one pure colour or an organ which emits a single pure musical note. For most broadcasting stations this peculiar and individual frequency lies somewhere between a million and half a million per second, though for the long wave stations like Daventry it is so low as 193,000 or 193 kilocycles. 中文

When we speak or sing or cause music to affect the microphone at a broadcasting studio the result is to cause the emitted vibrations, which are called the *carrier waves*, to fluctuate in height or wave amplitude, but does not alter the number of waves sent out per second. It is like altering the height or size of the waves on the surface of the sea without altering the distance from crest to crest which is called the

wave-length. 中文

Suppose the broadcasting station emits a carrier wave of frequency n and let $p = 2\pi n$. Then we may express the amplitude a of this wave at any time t by the function $a = A \sin pt$ where A is the maximum amplitude. If on this we impose a low frequency oscillation due to a musical note of frequency m and let $2\pi m = q$, then we can express the modulated vibration by the function

$$a = A \cos qt \sin pt$$

But by a well-known trigonometrical theorem this is equal to

$$\frac{A}{2} \{ \sin(p + q)t + \sin(p - q)t \} ,$$

and thence may be supposed to be equivalent to the simultaneous emission of two carrier waves of frequency $n + m$ and $n - m$. 中文

If the imposed note or acoustic vibration is very complex in form, then in virtue of Fourier's theorem it may be resolved into the sum of a number of simple harmonic terms of form $\cos qt$, and each of these may be considered to be equivalent to a pair of co-existent carrier waves. Hence the complex modulation of a single frequency carrier wave might be imitated by the emission of a whole spectrum or multitude of simultaneous carrier waves of frequencies ranging between the limits $n + N$ and $n - N$, where n is the fundamental carrier frequency and N is the maximum acoustic frequency occurring and $2N$ is the width of the wave band. This, however, is a purely mathematical analysis, and this band of multiple frequencies does not exist, but only a carrier wave of one single frequency which is modulated in amplitude regularly or irregularly. 中文

If the sounds made to the microphone at the broadcasting station are very complex, such as those due to instrumental music or speech, then in virtue of this mathematical theorem the very irregular fluctuations

in amplitude of the single carrier wave can be imitated if we suppose the station to send out simultaneously a vast number of carrier waves of various frequencies lying between certain limits called the “width of the wave band”. [中文](#)

This, however, is merely a mathematical artifice similar to that employed when we resolve a single force or velocity in imagination into two or more component forces. Thus, if we consider a ball rolling down an inclined plane and desire to know how far it will roll in one second, we can resolve the single vertical gravitational force on the ball into two components, one along the plane and one perpendicular to it. But this is merely an ideal division for convenience of solution of the problem; the actual force is one single force acting vertically downwards. Similar reasoning is true with regard to wireless telephony. What happens, as a matter of fact, is that the carrier wave of one single constant frequency suffers a variation in amplitude according to a certain regular or irregular law. There are no multiple wave-lengths or wave bands at all. [中文](#)

The receiver absorbs this radiation of fluctuating amplitude and causes the direct current through the loud speaker to vary in accordance with the fluctuations of amplitude of the carrier wave; the carrier wave vibrations being rectified by the detector valve. [中文](#)

The same thing takes place in the case of wireless transmission in television. The scanning spot passes over the object and the reflected light falls on the photoelectric cells and creates in them a direct current which varies exactly in proportion to the intensity of the reflected light. This photoelectric current is employed to modulate the amplitude of a carrier wave, and the neon lamp at the receiving end translates back these variations of carrier wave amplitude into variations in the cathode light of the neon tube. [中文](#)

There is neither in wireless telephony nor in television any question of

various bands of wavelength. There is nothing but a carrier wave of one single frequency which experiences change of amplitude. The whole question at issue then is, what range in amplitude is admissible? [中文](#)

In the case of television it is usual for critics of present achievements to say that good or satisfactory television cannot be achieved within the limits of the nine kilocycle band allowed. But there is in reality no wave band involved at all. It is merely a question of what change in amplitude in a given carrier wave can be permitted without creating a nuisance. [中文](#)

It is something like the question: How loud can you whisper to your next neighbour at a concert or theatre without being considered to be a nuisance? People do whisper in this way, and provided not too loudly, it is passed over. But if anyone is so ill-mannered as to speak too loudly he is quickly called to order, or turned out. [中文](#)

It is, however, not an easy thing to define a limit to wave amplitudes. They are measured in microvolts per metre and are difficult to measure. But a wave-length is easy to define in kilocycles or in metres, and hence the method has been adopted of limiting emission to an imaginary band of wavelengths which, however, do not exist. [中文](#)

The definition is imperfect or elusive. It is something like the old-fashioned definition of metaphysics as “a blind man in a dark room groping for a black cat which isn’t there”. Similarly, the supposed wave band is not there. All that is there is a change, gradual or sudden, in the amplitude of the carrier wave. It is clear, then, that sooner or later we shall have to modify our code of wireless laws.

[中文](#)

We have no reason for limiting the output of our broadcasting stations to some imaginary wave band of a certain width, say nine kilocycles or whatever may be the limiting width, but we have reason for

limiting the range of amplitude of the carrier waves sent out. 中文

Some easily applied method will have to be found of defining and measuring the maximum permissible amplitude of the carrier waves as affected by the microphone or other variational appliance. It may perhaps be thought that an unnecessary fuss is here being made on what may be regarded as simply a way of explaining things, but experience in other arts shows how invention may be greatly retarded by unessential official restrictions. Consider, for example, the manner in which mechanical traction was retarded in Great Britain for years by ridiculous regulations limiting the speed of such vehicles on highway roads. The only restrictions that should be imposed are those absolutely necessary in the interests of public safety or convenience, and all else tend to throttle and retard invention and progress. 中

文

(125, 92-93; 1930)

无线传输的“波带”理论

弗莱明

在本文中安布罗斯·弗莱明对应用于无线电话和电视的波通信有不同的理解。在这两项技术中，装置把信号编译成振幅调制的载波。在傅立叶分析中，我们可以认为得到的波占据了载波频率附近的一个频“带”。大家通常要考虑的是这些频带如何分配，哪些频带能够被允许等等。但弗莱明认为人们对频带的过分关注掩盖了振幅的作用。太大的振幅可能会导致不同传输过程之间的干扰，就像在戏院中大声讲话带来的麻烦一样。弗莱明指出，对振幅而不是频带的关注将会帮助我们避免在应用这项新技术时遇到不必要的麻烦或限制。 [英文](#)

在科学史上，我们遇到的许多科学理论或解释被广泛接受并应用的情况，并不是因为它们能够被证明是真理，而是因为它们为某些科学现象提供了简单、易于被理解并且似乎合理的解释。大多数人并不能透过复杂现象发现真理，因此也就乐于不加质疑地接受某种能够便捷地解释复杂现象的假说。 [英文](#)

然而，简单的理解并不是自然界的基本特征，也不能随即得到，即不会因为我们想象一种能够解释某些自然现象的机制，它就以那种方式来实现。在关于无线电话传输以及电视的某种理论中，存在一种广为流传的认识，即为了达到可靠的良好效果，必须限制在具有确定宽度的“波带”内操作。这种观点虽然已被广泛接受，但我们有理由认为，这只是一类数学虚构，并不能与自然界的任何现实相对应。 [英文](#)

让我们考虑这是如何产生的。我们从所有的无线电话发射台发出一个具有确定的恒定频率（以千周表示）的电磁辐射。伦敦2LO电台按照这种方式以842千周的频率进行广播。这意味着它每秒内发出842,000次

电子振荡或842,000个波。每个广播站已分配到一个确定的振荡频率，而且不允许偏离此频率。 [英文](#)

这就像一座发出单色光的灯塔或一个发出单一音符的风琴。对于大多数广播站而言，这类特有的专用频率位于每秒50万~100万之间，然而对于类似达文特里这样的长波站，它的频率低至193,000，或193千周。 [英文](#)

当我们在播音室里对着麦克风说话、唱歌或放出音乐，都会导致发射振荡的产生，这被称作载波，它会使波的高度或波幅出现起伏，但并不改变每秒钟发出的波数。这类似于只改变海面上波浪的高度或大小，而不改变被称作波长的从波峰到波峰的距离。 [英文](#)

假定广播站发射一个频率为 n 的载波，并令 $p = 2\pi n$ 。我们通过函数 $a = A \sin pt$ 表示在任意时刻 t 这个波的振幅 a ，其中 A 是最大振幅。如按这种方式，我们施加一个由频率为 m 的音符引起的低频振荡，并令 $2\pi m = q$ ，则我们可以通过下面的函数方程表示调制振荡

$$a = A \cos qt \sin pt$$

通过人们熟知的三角定理，上式等于

$$\frac{A}{2} \{ \sin(p+q)t + \sin(p-q)t \} ,$$

因此可以认为其等效于同时发射频率为 $n + m$ 和 $n - m$ 的两个载波。

[英文](#)

如果施加的音律或声音振荡在形式上很复杂，那么利用傅立叶定理，我们可将其分解为如 $\cos qt$ 形式的许多简谐项之和，可以等效地认为其中每一项都是一对共存的载波。因此单频载波的复杂调制可以用整个谱的发射或大量频率在 $n + N$ 到 $n - N$ 之间的同步载波来模拟，其中 n 是基本载波频率，而 N 是出现的最大声波频率， $2N$ 是波带的宽度。然而，这是纯数学分析，这个多频波带并不存在，而只存在单频的载波，可以对其振幅进行规则或不规则的调制。 [英文](#)

如果向广播站里的麦克风发出的声音非常复杂，例如乐器发出的声

音或讲话的声音，那么根据这个数学原理，我们可以假定广播站里同时发出大量频率被限定在“波带宽度”之内的载波来模拟单个振幅不规则波动的载波。 [英文](#)

然而，这仅是一个数学技巧，类似于我们在假想中将单个力或速度分解为两个或更多个分量。因此，如果我们考虑一个沿倾斜平面滚下的球，并要求知道球在一秒钟内滚动多远，我们就可以将球受到的单一的垂直引力分解为两个分量，分别与平面平行和垂直。但这只是便于解决问题的一个理想的分解；实际的力仍只是作用方向垂直向下的单个力。对于无线电也存在着相似的思考过程。事实上，发生的情况是，一个单一恒定频率的载波按照某种规则或不规则的规律在振幅上发生变化。根本不存在多重的波长或波带。 [英文](#)

接收器吸收了这类振幅振荡变化的辐射，并使通过扬声器的直流按照载波振幅的振荡变化而变化；载波的振动通过检测器的电子管进行整流。 [英文](#)

对于电视的无线传输来说也存在相同的情况。扫描点在物体上扫描，而反射光落在光电元件上，并在其中产生了与反射光强度精确成正比变化的直流。这个光电流用于载波振幅的调制，在接收端的氖灯会将这些载波振幅的变化转换回氖管的阴极光的变化。 [英文](#)

在无线电和电视中均不存在各种不同波带的问题。只是存在振幅被调制的单频载波。那么争论的全部问题就是，可以允许振幅在什么范围内变化呢？ [英文](#)

对于电视而言，批评现有成果的评论者们通常会提出，在允许的9千周的限制范围内，性能良好的或令人满意的电视不可能实现。但实际上根本不存在所谓的波带。这仅仅是一个在不产生干扰的情况下可以允许给定的载波中振幅如何变化的问题。 [英文](#)

这就类似于如下的问题：在音乐厅或剧场中你可以用多大的声音悄悄对邻座说话而不至于影响其他人呢？人们以这种方式耳语，并保持声音不是很大，这样可以不被注意。但是如果任何人非常不礼貌地用很大的声音说话，他很快就会被要求保持安静或被逐出会场。 [英文](#)

然而，确定波幅的调制范围并不是件容易的事情。它们以每米微伏的数量级来进行计量，并且是很难被测定的。但波长很容易用千周或米来定义，因此现已采用的方法是将发射限定到虚构的波带范围内，然而，这个波带实际上并不存在。 [英文](#)

这样的定义是不完善的，或者说是难以理解的。这有点像形而上学的老式定义，如“一个在暗室里摸索一只并不存在的黑猫的盲人”。类似地，我们假设的波带并不存在。存在的只是载波中振幅逐步或突然的变化。显然，总有一天我们将不得不修改我们的无线通信的编码规则。

[英文](#)

我们没有理由将我们的广播电台的输出限制在某种确定宽度的假想波带内，比如说9千周或其他任何限制范围，但我们有理由限定输出载波振幅的范围。 [英文](#)

我们必将找到某些易于应用的方法，用来定义及测量被麦克风或其他有变化的设备影响的载波的最大允许振幅。也许有人会认为，这只是事物的一种解释方式，没有必要像我们这样小题大做，但其他技术中的经验表明，不必要的官方限定是如何使可能的重大发明被推迟的。考虑一下这样的事例，机械牵引在英国的发展多年受阻，正是由于制定了荒谬的法规限制公路上的这类车辆的速度而导致的。唯一应该加以限制的，是那些出于公共安全性或便利性的考虑绝对必要的方面，而其他所有方面的限制往往会扼杀并妨碍发明和进步。 [英文](#)

（沈乃澂 翻译；李军刚 审稿）

Electrons and Protons

Paul Dirac was one of the most creative physicists of the early twentieth century. In 1932 he was appointed Lucasian professor at Cambridge University, and his theory unifying quantum mechanics with Einstein's theory of special relativity won him the 1933 Nobel Prize in physics. Here *Nature* reports on one of the implications of this theory, as Dirac outlined in a paper in the *Proceedings of the Royal Society*. His equations predicted "electrons of negative energy", which meant, of positive charge. The report echoes Dirac's initial suspicion that these predicted positively charged particles would behave like protons, but they soon proved to be "positive electrons" or positrons, made of antimatter. [中文](#)

A theory of positive electricity has been put forward by Dr. P. A. M. Dirac in the January number of the *Proceedings of the Royal Society*. The relativity quantum theory of an electron leads to a wave equation which possesses solutions corresponding to negative energies—the energy of the electron of ordinary experiment being reckoned as positive—and although there are serious difficulties encountered in any immediate attempt to associate these negative states with protons, the existence of positive electricity can be predicted by a fairly direct line of argument. Since the stable states of an electron are those of lowest energy, all the electrons would tend to fall into the negative energy states—with emission of radiation—were it not for the Pauli exclusion principle, which prevents more than one electron from

going to any one state. If, however, it is assumed that “there are so many electrons in the world that... all the states of negative energy are occupied except perhaps a few...”, it may be supposed that the infinite number of electrons present in any volume will remain undetectable if uniformly distributed, and only the few “holes”, or missing states of negative energy will be amenable to observation. The step is then made of regarding these “holes” as “*things of positive energy*” which are identified with the protons. A difficulty now arises in ordinary electromagnetic theory which apparently has to cope with the presence of negative electricity of infinite density; this is met by supposing that for ordinary purposes volume-charges must be measured by departures from a “normal state of electrification”, which is “the one where every electronic state of negative energy and none of positive energy is occupied.” The problem of the large mass of the proton, as compared with that of the electron, is not discussed in detail, but a possible line of attack is indicated. Dr. Dirac has included the minimum of mathematical analysis in this paper, which can be followed in all essential points by anyone acquainted with the principles of the quantum theory. 中文

(125, 182; 1930)

电子和质子

保罗·狄拉克是20世纪初最有建树的物理学家之一。1932年，他被聘任为剑桥大学的卢卡斯教授。他因提出能将量子力学与爱因斯坦的狭义相对论统一起来的理论而获得了1933年的诺贝尔物理学奖。在发表于《皇家学会学报》的一篇论文中，狄拉克对他的理论所蕴含的一个推断进行了概述，《自然》的这篇文章报道的正是这些。狄拉克的方程预测出“具有负能量的电子”，即带正电荷的电子。狄拉克最初认为，这些被预测到的带正电荷的粒子的行为方式与质子类似，这篇报道再次复述了这一观点，但不久之后，这些粒子就被证明是组成反物质的“正电子”。 [英文](#)

在1月的《皇家学会学报》上，狄拉克博士提出了正电子理论。他通过电子的相对论量子理论导出了一个波动方程，而这个波动方程包含相应于负能量的解（普通实验中电子的能量被认为是正的）。尽管将这种负能态与质子联系起来的尝试遇到了很多困难，但是，通过非常直接的论证可以预言正电子的存在。因为电子的稳定态是能量最低的态，所以伴随着发射辐射，所有电子都将落入负能态，但是这与泡利不相容原理不同，这一原理规定不可能有多于一个的电子处于任何一个相同的状态。然而，如果假设“世界上有非常多的电子以至于除了极少的负能态以外，几乎所有的负能态都被占据了”，那么可以推测，这些存在于负能态体系中的无数个电子将不会被探测到（若电子是均匀分布的），而仅有极少的“空穴”或遗漏的负能态可以很容易地被观察到。接下来他把这些“空穴”视为与质子相同的“具有正能量的物质”。密度无限大的负电的出现使普通电磁学理论遇到了困难。不过，当假定一般情况下必须通过“带电的正常状态”的偏离来测量体电荷时，便可以解决这个难题，所谓带电的正常状态是指“每一个具有负能量的电子态均被占据而没有一个正能态被占据的状态”。在这篇文章中，他并没有详细讨论质子质量比电

子质量大这一问题，但是却提出了一种可能的解决思路。狄拉克博士的论文仅涉及少量数学分析，这就使任何一个学习过量子理论基本原理的人都能看懂这些数学分析的要点。 [英文](#)

（王锋 翻译；李淼 审稿）

Artificial Disintegration by α -particles

J. Chadwick and G. Gamow

In 1919 Ernest Rutherford had shown that alpha particles fired into nitrogen gas could create hydrogen, apparently because the particles kick a proton out of the nucleus while being themselves captured. Rutherford called the process “artificial disintegration” (popularly, splitting) of the atom. Here James Chadwick and George Gamow suggest that protons might also be produced without the alpha particle entering the nucleus. Gamow went on to propose that protons, with only half the charge of alpha particles, might approach the positively charged nucleus more easily. That idea stimulated work at Cambridge on a high-voltage device to accelerate protons to high energies, leading to the first induced splitting of a lithium nucleus by proton bombardment by John Cockroft and Ernest Walton. [中文](#)

IT is commonly assumed that the process of artificial disintegration of an atomic nucleus by collision of an α -particle is due to the penetration of the α -particle into the nuclear system; the α -particle is captured and a proton is emitted. [中文](#)

On general grounds it seems possible that another process may also occur, the ejection of a proton without the capture of the α -particle.

[中文](#)

Consider a nucleus with a potential field of the type shown in Fig. 1, where the potential barrier for the α -particle is given by the full line and that for the proton by the dotted line. Let the stable level on which the proton exists in the nucleus be $-E_p^0$ and the level on which the α -particle remains after capture be $-E_\alpha^0$. 中文

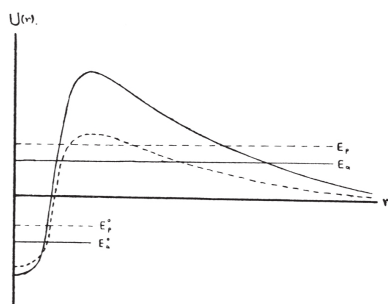


Fig. 1 中文

If an α -particle of kinetic energy E_α penetrates into this nucleus and is captured, the energy of the proton emitted in the disintegration will be $E_p = E_\alpha + E_\alpha^0 - E_p^0$, neglecting the small kinetic energy of the recoiling nucleus. If the nucleus disintegrates without capture of the α -particle, the initial kinetic energy of the α -particle will be distributed between the emitted proton and the escaping α -particle (again neglecting the recoiling nucleus). The disintegration protons may have in this case any energy between $E_p = 0$ and $E_p = E_\alpha - E_p^0$. 中文

Thus, if both these processes occur, the disintegration protons will consist of two groups: a continuous spectrum with a maximum energy less than that of the incident α -particles and a line spectrum with an energy greater or less than that of the original α -particles according as $E_\alpha^0 > E_p^0$ or $E_\alpha^0 < E_p^0$, but in either case considerably greater than the upper limit of the continuous spectrum (see Fig. 2). 中文

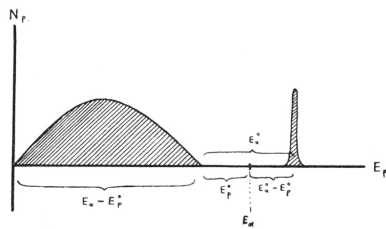


Fig. 2 中文

In some experiments of one of us in collaboration with J. Constable and E. C. Pollard, the presence of these two groups of protons appears quite definitely in certain cases, for example, boron and aluminium. A full discussion of these and other cases of disintegration will be given elsewhere, but it may be noted that the existence of groups of protons has already been reported by Bothe and by Pose. In general the experimental results suggest that with incident α -particles of energy about 5×10^6 volts (α -particles of polonium) the process of non-capture is several times more frequent than the process of capture.

中文

It is clear that, if our hypothesis is correct, accurate measurement of the upper limit of the continuous spectrum and of the line will allow us to estimate the values of the energy levels of the proton and α -particle in the nucleus. In the case of aluminium bombarded by the α -particles of polonium the protons in the continuous spectrum have a maximum range of 32 cm and those of the line spectrum a range of 64 cm. These measurements give the following approximate values for the energy levels:

$$E_p^0 = 0.6 \times 10^6 \text{ e volts, and } E_\alpha^0 = 2 \times 10^6 \text{ e volts.}$$

中文

On the wave mechanics the probability of disintegration of both types is given by the square of the integral

$$W = \int f(r_{\alpha,p}) \cdot \psi_\alpha \cdot \psi_p \cdot \phi_\alpha \cdot \phi_p \cdot dV \cdot dV' \quad (1)$$

where $f(r_{\alpha, p})$ is the potential energy of an α -particle and a proton at the distance $r_{\alpha, p}$ apart, and the wave functions ψ_{α}, ψ_p represent the solutions for the α -particle and proton before and ϕ_{α}, ϕ_p after the disintegration. In calculating the integral (1) we must develop the incident plane wave of the α -particle into spherical harmonics corresponding to different azimuthal quantum numbers of the α -particle, and deal with each term separately. 中文

In the case of capture of the α -particle the estimation of (1) can be carried out quite simply. It can be shown that the effect of the higher harmonics is very small, and that the disintegration is due almost entirely to the direct collisions. Thus we obtain for the probability of disintegration

$$W_1^2 = \frac{A}{v_{\alpha}^2} \cdot e^{-\frac{8\pi^2 e^2}{h} \cdot \frac{Z}{v_{\alpha}}} \cdot e^{-\frac{4\pi^2 e^2}{h} \cdot \frac{Z}{v_p}} \quad (2)$$

where v_{α} and v_p are the velocities of the initial α -particle and the ejected proton respectively. Since only the first harmonic is important in disintegration of this type, it is to be expected that the protons will be distributed nearly uniformly in all directions. 中文

When the α -particle is not captured the disintegrations will arise mainly from collisions in which the α -particle does not penetrate into the nucleus. For disintegration produced in this way the higher harmonics become of importance. The probability of disintegration can be roughly represented by the formula

$$W_2^2 = B \cdot e^{-\frac{8\pi^2 e^2}{h} \cdot Z \left(\frac{1}{v'_{\alpha}} - \frac{1}{v_{\alpha}} \right)} \cdot e^{-\frac{4\pi^2 e^2}{h} \cdot \frac{Z}{v_p}} \quad (3)$$

where v'_{α} is the velocity of the α -particle after the collision, and B is a function of the angle of ejection of the proton. The protons of the continuous spectrum will not be emitted uniformly in all directions. According to the expression (3) the distribution with energy of the protons in the continuous spectrum will have a maximum value for an energy of ejection of about 0.3 of the upper limit, and will vanish for

zero energy and at the upper limit. [中文](#)

More detailed accounts of the experimental results and of the theoretical calculations will be given shortly. [中文](#)

(126, 54-55; 1930)

J. Chadwick, G. Gamow: Cavendish Laboratory, Cambridge, June 18.

α 粒子引发的人工衰变

查德威克，伽莫夫

1919年，欧内斯特·卢瑟福发现 α 粒子射入氮气后可以产生氢，这显然是因为 α 粒子被俘获的同时把一个质子赶出了原子核。卢瑟福把这个过程称作原子的“人工衰变”（更通俗地说是裂变）。詹姆斯·查德威克和乔治·伽莫夫在本文中提出，在没有 α 粒子进入原子核的情况下我们也可以得到质子。伽莫夫还指出，质子所带电荷数只有 α 粒子的一半，它有可能更容易接近带正电的原子核。这种观点推动了剑桥大学的约翰·考克饶夫和欧内斯特·瓦耳顿的工作，他们用高压装置把质子加速到很高的能量，然后通过质子轰击首次实现了锂核的诱导裂变。 [英文](#)

通常的假设是，一个 α 粒子与原子核发生碰撞的人工衰变过程，是由 α 粒子穿透到核系统内部导致的；在 α 粒子被俘获的同时，也会发射出一个质子。 [英文](#)

按照通常的观点，另外一种过程也可能发生，即在没有俘获 α 粒子的情况下，释放出一个质子。 [英文](#)

研究一个处于图1所示的势场条件下的核，其中实线代表 α 粒子的势垒，虚线代表质子的势垒。令原子核中质子的稳态能级为 $-E_p^\circ$ ，被俘获后的 α 粒子的能级为 $-E_\alpha^\circ$ 。 [英文](#)

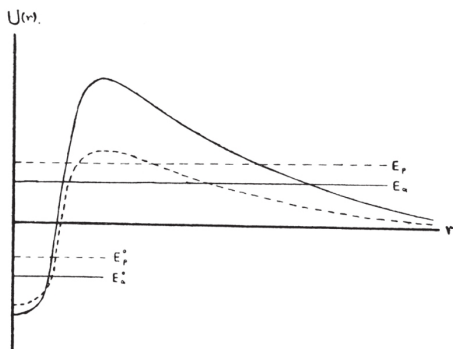


图1 英文

如果动能为 E_α 的 α 粒子穿透到这个核的内部并被俘获，那么衰变中发射出的质子的能量是 $E_p = E_\alpha + E_\alpha^0 - E_p^0$ ，这里忽略了此过程中反冲核的微小动能。如果在核衰变的过程中没有俘获 α 粒子， α 粒子的初始动能将在发射出的质子与逃逸的 α 粒子之间分配（再次忽略反冲核）。

在这种情况下，衰变质子的能量可能是 $E_p = 0$ 与 $E_p = E_\alpha - E_p^0$ 之间的任意值。 英文

因此，如果这两种过程都存在，那么衰变的质子将由两部分组成：最大能量小于入射 α 粒子能量的连续谱和能量大于或小于初始 α 粒子能量的线状谱，相当于 $E_\alpha^0 > E_p^0$ 或 $E_\alpha^0 < E_p^0$ ，但对于这两种情况中的任何一种，能量都比连续谱的上限大很多（见图2）。 英文

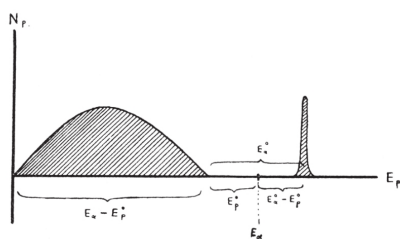


图2 英文

在我们中的一位与康斯特布尔和波拉德合作进行的一些实验中，在某些情况下这两组质子的存在会非常明确地表现出来，比如，硼和铝的情况。关于这些以及其他一些衰变的情况将会在别的地方给出全面的讨论，但可以注意到的是，博特和波泽已经报道了多组质子的存在。一般而言，实验结果显示，当入射 α 粒子（钋的 α 粒子）的能量约为 5×10^6 电子伏时，非俘获过程发生的频率比俘获过程高出几倍。 英文

显然，如果我们的假设是正确的，那么对连续谱和线状谱上限的精确测量将使我们能对原子核中的质子和 α 粒子的能级数值进行估计。在用钋的 α 粒子轰击铝的情况下，在连续谱中质子的最大范围为32厘米，而在那些线状谱中的范围为64厘米。由这些测量得到的能级近似值如下：

$$E_p^o = 0.6 \times 10^6 \text{ 电子伏}, E_a^o = 2 \times 10^6 \text{ 电子伏}.$$

英文

根据波动力学，两种类型的衰变概率由积分的平方给出

$$W = \int f(r_{\alpha, p}) \cdot \psi_{\alpha} \cdot \psi_p \cdot \phi_{\alpha} \cdot \phi_p \cdot dV \cdot dV' \quad (1)$$

式中 $f(r_{\alpha, p})$ 是相距为 $r_{\alpha, p}$ 的一个 α 粒子和一个质子之间的势能，波函数 ψ_{α} 和 ψ_p 表示 α 粒子和质子在衰变前的解， ϕ_{α} 和 ϕ_p 表示它们在衰变后的解。在计算积分（1）时，我们必须将 α 粒子的入射平面波展开为对应于 α 粒子不同角量子数的球谐函数的形式，并对每一项分别处理。

英文

在俘获 α 粒子的情况下，对（1）式进行估算非常简单。可以看到的是，高次谐波的效应很小，衰变几乎全部由直接碰撞产生。因此我们可以得到衰变概率

$$W_1^2 = \frac{A}{v_{\alpha}^2} \cdot e^{-\frac{8\pi^2 e^2}{h} \cdot \frac{Z}{v_{\alpha}}} \cdot e^{-\frac{4\pi^2 e^2}{h} \cdot \frac{Z}{v_p}} \quad (2)$$

式中 v_{α} 和 v_p 分别是初始 α 粒子和发射出的质子的速度。因为在这类衰变中，只有一次谐波起主要作用，所以可以认为质子在所有方向上都是均匀分布的。

英文

当 α 粒子未被俘获时，衰变将主要通过 α 粒子并不穿透到核内的碰撞产生。在由这种方式产生的衰变过程中，高次谐波开始起主要作用。衰变概率可以通过下述公式近似地表示

$$W_2^2 = B \cdot e^{-\frac{8\pi^2 e^2}{h} \cdot Z \left(\frac{1}{v_{\alpha}'} - \frac{1}{v_{\alpha}} \right)} \cdot e^{-\frac{4\pi^2 e^2}{h} \cdot \frac{Z}{v_p}} \quad (3)$$

式中 v_{α}' 是碰撞后 α 粒子的速度， B 是质子发射角度的函数。连续谱中的质

子在各个方向上的发射并不均匀。根据表达式（3），连续谱中质子的能量分布，在约为上限的0.3处其发射能量达到最大值，而在上限处突然变为零。 [英文](#)

不久之后，我们将给出关于实验结果和理论计算的更详细的解释。

[英文](#)

（沈乃澂 翻译；江丕栋 审稿）

Fine Structure of α -rays

G. Gamow

George Gamow was a Russian scientist who left the Soviet Union in 1932 and worked at several Western European universities until moving to the United States before the Second World War. He made a powerful impression by his versatility as a scientist, his capacity to write clearly for the general public and his engagement in public causes such as advocacy of building nuclear weapons in the United States. This brief letter offers an explanation of why γ -rays emitted by radioactive atoms may have a variety of energies. [中文](#)

IT is usually assumed that the long range α -particles observed in C' -products of radioactive series correspond to different quantum levels of the α -particle in the nucleus. If after the preceding β -disintegration the nucleus is left in an excited state with the α -particle on one of the levels of higher energy, one of the two following processes can take place: either the α -particle will cross the potential barrier surrounding the nucleus and will fly away with the total energy of the excited level (long range α -particle), or it will fall down to the lowest level, emitting the rest of its energy in the form of electromagnetic radiation (γ -rays), and will later fly away as an ordinary α -particle of the element in question. Thus there must exist a correspondence between the different long range α -particles and the γ -rays of the preceding radioactive body. If p is the relative number of nuclei in the excited state, λ the corresponding decay constant, and θ the probability of

transition of the nucleus from the excited state to one of the states of lower energy with emission of energy (in form of γ -quanta or an electron from the electronic shells of the atom), the relative number of long range α -particles must be $N = p \frac{\lambda}{\theta}$. Knowing the number of α -particles in each long range group and calculating, from the wave mechanical theory of radioactive disintegration, the corresponding values of λ , we can estimate for each group the value θ/p , giving a lower limit for the probability of γ -emission. For example, for thorium-C' possessing besides the ordinary α -particles also two groups of long range α -particles, we have for transition probabilities from two excited states to the normal state $\theta_1 < 0.4 \times 10^{12} \text{ sec}^{-1}$ and $\theta_2 < 2 \times 10^{12} \text{ sec}^{-1}$, which is the right order of magnitude for the emission of light quanta of these energies. With decreasing energy λ decreases much more rapidly (exponentially) than θ , so that the number of long range α -particles from the lower excited levels will be very small. (From this point of view we can also easily understand why the long range α -particles were observed only for C'-products for which the energy of normal α -particles is already much greater than for any other known radioactive element.) 中文

A difficulty arises with the recent experiments of S. Rosenblum (C. R., p. 1,549; 1929; p. 1,124; 1930), who found that the α -rays of thorium-C consist of five different groups lying very close together. The energy differences and intensities of the different groups relative to the strongest one (α_0) are, according to Rosenblum:

$$E\alpha_1 - E\alpha_0 = +40.6 \text{ kv } I\alpha_1 = 0.3$$

$$E\alpha_2 - E\alpha_0 = -287 \dots I\alpha_2 = 0.03$$

$$E\alpha_3 - E\alpha_0 = -442 \dots I\alpha_3 = 0.02$$

$$E\alpha_4 - E\alpha_0 = -421 \dots I\alpha_4 = 0.005$$

If we suppose that these groups are due to α -particles escaping from different excited quantum levels in the nucleus, we meet with very serious difficulties. The decay constant λ for the energy of thorium-C fine structure particles is very small ($\lambda \sim 10^{-2} \text{ sec}^{-1}$), and in order to explain the relatively great number of particles in different groups we must assume also very small transition probabilities. We must assume that thorium-C nucleus can stay in an excited state without emission of energy for a period of half an hour! 中文

We can, however, obtain the explanation of these groups by assuming that we have here a process quite different from the emission of long range α -particles. Suppose that two (or more) α -particles stay on the normal level of the thorium-C nucleus. It can happen that after one of the α -particles has escaped the nucleus will remain in an excited state with the other particle on a certain level of higher energy. (In this case the energy of the escaping α -particle will be smaller than the normal level and obviously will not correspond to any quantum level inside the nucleus.) From the excited state the nucleus (thorium-C'' now) can afterwards jump down to the normal level, emitting the energy difference in form of a γ -quantum. 中文

Thus the relative number of different groups will not depend on the probability of γ -emission but only on the transition integral:

$$W = \int f(r_{1,2}) \psi_{E_0}(\alpha_1) \psi_{E_0}(\alpha_2) \psi_{E_n}(\alpha_1) \psi_{E_{a_n}}(\alpha_2) dv_1 dv_2$$

where $f(r)$ is the interaction energy of two α -particles at a distance r apart, ψ_{E_0} and ψ_{E_n} the eigenfunctions of an α -particle in the normal and n^{th} excited states, and $\psi_{E_{a_n}}$ the eigenfunction of an escaping α -particle with the energy: $E_{a_n} = E_0 - (E_n - E_0)$. 中文

According to this scheme, the γ -rays corresponding to different fine structure groups of thorium-C must be observed as γ -rays of thorium-C (ejecting electrons from $K, L, M, \dots$ shells of the thorium-C''-atom) and not as the rays of thorium-B, as we would expect in the case of long

range particle explanation. The level scheme of the thorium-C''-nucleus as given by fine structure energies is represented in Fig. 1.

中文

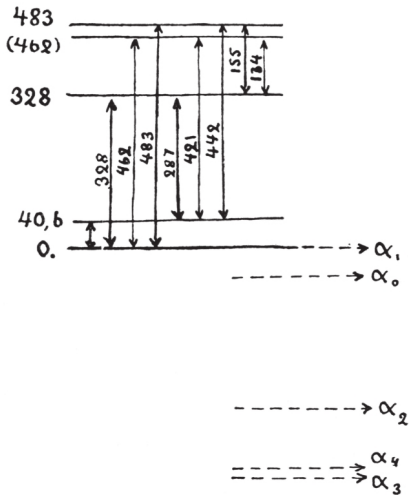


Fig. 1 中文

In the observed γ -ray spectra of thorium-C + C'' (Black, *Proc. Roy. Soc.*, pp. 109–166; 1925) we can find lines with the energies: 40.8; 163.3; 279.4; 345.8; 439.0; 478.8; 144.6 kv fitting nicely with the energy differences in Fig. 1. 中文

Thus we see that the fine structure group of highest energy corresponds to the normal level of the nucleus, while the other groups are due to the ordinary α -particles which have lost part of their energy, leaving the nucleus in an excited state. 中文

I am glad to express my thanks to Dr. R. Peierls and Dr. L. Rosenfeld for the opportunity to work here. 中文

(126, 397; 1930)

α 射线的精细结构

伽莫夫

乔治·伽莫夫是一位俄国科学家，他于1932年离开苏联，在几所西欧的大学里工作。第二次世界大战爆发前夕，他去了美国。他是一位多才多艺的科学家，为公众撰写的普及读物非常清晰易懂，他在美国投身于公众事业，支持原子武器，这些都给人们留下了深刻的印象。在这篇简短的快报文章中，他解释了为什么放射性原子发射出的 γ 射线可能具有不同的能量。 [英文](#)

我们通常假设， C 放射系列产物中观测到的长程 α 粒子对应于原子核中 α 粒子的不同量子能级。如果在 β 衰变之后，原子核处于 α 粒子占据某个更高能级的激发态，那么就可能发生下面两个过程中的一个：或者是 α 粒子穿过原子核周围的势垒，携带激发态的所有能量而逃逸（长程 α 粒子）；或者是 α 粒子降至最低能级，将剩余能量以电磁辐射（ γ 射线）的形式发射出去，然后再以普通 α 粒子的形式逃逸出该原子核。这样，在长程 α 粒子和之前的放射体放出的 γ 射线之间就应该存在某种关联。如果 p 是处于激发态的原子核的相对数量， λ 是相应的衰减常数， θ 是原子核从激发态跃迁到某个低能态并辐射出能量（以 γ 量子或者是从该原子电子壳层中发射出的电子的形式）的概率，那么长程 α 粒子的相对数量就是 $N = p \frac{\lambda}{\theta}$ 。我们已经知道了每一个长程组内的 α 粒子数量，并且可以通过辐射衰变的波动力学理论计算出相应的 λ 值，那么我们就可以估算出每一组的 θ/p 值，得到一个 γ 辐射发生概率的下限。比如，在钍 C' 的衰变中，除释放普通的 α 粒子之外，还有两组长程 α 粒子，对于从这两个激发态跃迁到正常态的概率，我们知道： $\theta_1 < 0.4 \times 10^{12} \text{秒}^{-1}$ ， $\theta_2 < 2 \times 10^{12} \text{秒}^{-1}$ ，这个数量级对于辐射这些能量的光子来说是合适的。当能量减小时， λ （呈指数减小）比 θ 减小的速度快很多，因此来自较低激发态的长程 α 粒子数量将会非常少。（这样看来，就不难理解为什么长

程 α 粒子只有在C的衰变产物中才会出现了，C过程产物中的正常 α 粒子的能量远远高于其他已知的任何放射性元素产生的能量。） [英文](#)

罗森布拉姆在最近的实验中遇到了一些困难（《法国科学院院刊》，1929年第1,549页，1930年第1,124页），他发现钍C放射的 α 射线是由非常接近的5个不同的组组成的。罗森布拉姆给出了其余各组相对于最强的那一组（ α_0 ）的能量差和强度：

$$E\alpha_1 - E\alpha_0 = +40.6 \text{ 千电子伏 } I\alpha_1 = 0.3$$

$$E\alpha_2 - E\alpha_0 = -287 \text{ 千电子伏 } I\alpha_2 = 0.03$$

$$E\alpha_3 - E\alpha_0 = -442 \text{ 千电子伏 } I\alpha_3 = 0.02$$

$$E\alpha_4 - E\alpha_0 = -421 \text{ 千电子伏 } I\alpha_4 = 0.0005$$

[英文](#)

如果我们假设这些组分是由于逃逸的 α 粒子曾处于原子核内的不同激发量子能级而形成的，那么我们将遇到很大的麻烦。钍C精细结构粒子的能量衰减常数 λ 非常小（ λ 约为 10^{-2} 秒 $^{-1}$ ），而且为了解释各组中何以有相对那么大量数的粒子，我们必须同时假设跃迁概率非常小。我们必须假设钍C原子核可以停留在激发态而不辐射能量长达半个小时！

[英文](#)

然而，如果我们设想一个完全不同于发射长程 α 粒子的过程，就可以解释这5组 α 粒子了。假设有两个（或者更多的） α 粒子处于钍C原子核的正常能级上。其中一个 α 粒子逃逸到原子核外后，原子核有可能还保持在激发态，因为剩下的 α 粒子可能处于某个能量较高的能级上。（在这种情况下，逃逸 α 粒子的能量低于正常能级，而且它显然与原子核内的任何量子能级都不相等。）随后原子核（这里是钍C''）可以从激发态跃迁到正常态，放出一个 γ 量子以释放两态之间的能量差。 [英文](#)

这样，不同组的相对数量将与 γ 辐射的概率无关，而只与跃迁积分相关：

$$W = \int f(r_{1,2}) \psi E_0(\alpha_1) \psi E_0(\alpha_2) \psi E_n(\alpha_1) \psi E_n(\alpha_2) dv_1 dv_2$$

式中, $f(r)$ 是两个 α 粒子在相距为 r 时的相互作用能, ψE_0 和 ψE_n 分别是 α 粒子在正常态和第 n 个激发态的本征函数, ψE_α 是能量为 $E_{\alpha_n} = E_0 - (E_n - E_0)$ 的逃逸 α 粒子的本征函数。 [英文](#)

按照这种解释, 对应于钍C不同精细结构组分的 γ 射线应该被看作是钍C的 γ 射线 (发射出的电子来自于钍C"原子的 K, L, M 等壳层), 而不能被看作是钍B的 γ 射线, 正如我们在解释长程粒子时预期的那样。图1中所示的钍C"原子核能级图画出了能量的精细结构。 [英文](#)

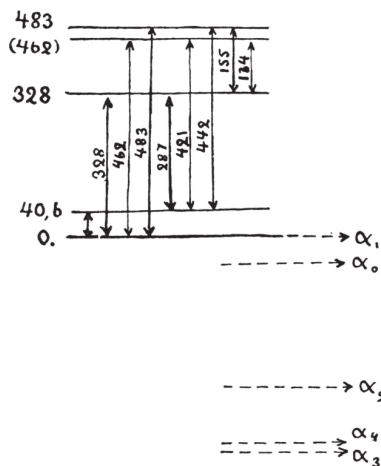


图1 [英文](#)

在实测的钍C和钍C"的 γ 射线能谱中 (布莱克, 《皇家学会学报》, 1925年, 第109 ~ 166页), 我们可以找到对应于以下能量的谱线: 40.8, 163.3, 279.4, 345.8, 439.0, 478.8, 144.6千电子伏, 这与图1中的能级差吻合得很好。 [英文](#)

我们可以看到, 能量最高的精细结构组分对应于原子核的正常态, 而其他组分则是由损失掉部分能量的普通 α 粒子离开处于激发态的原子核造成的。 [英文](#)

我非常感谢佩尔斯博士和罗森菲尔德博士给我提供在这里工作的机会。 [英文](#)

(王静 翻译；江丕栋 审稿)

The Proton*

P. A. M. Dirac

Here English physicist Paul Dirac describes his prediction, reported earlier in another journal, that electrons may have “negative energy” and consequently positive charge. This prediction followed from Dirac’s “relativistic” quantum theory, which made quantum mechanics compatible with special relativity. The “positive electrons” appear as “holes” in a pervasive electron sea. Dirac suspects they behave as protons, but there are problems with that: protons have very different masses from electrons, and the electrons and holes were predicted to annihilate. Dirac alludes to an idea of J. Robert Oppenheimer that a positive electron may in fact be a different particle with the mass of an electron. And so it later proved: they were positrons, anti-matter versions of electrons. [中文](#)

MATTER is made up of atoms, each consisting of a number of electrons moving round a central nucleus. It is likely that the nuclei are not simple particles, but are themselves made up of electrons, together with hydrogen nuclei, or protons as they are called, bound very strongly together. There would thus be only two kinds of simple particles out of which all matter is built, the electrons, each carrying a charge $-e$, and the protons, each carrying a charge $+e$. [中文](#)

It should be mentioned here that there is a difficulty in this point of view provided by the nitrogen atom. One can infer from the charge

and mass of the nitrogen nucleus that it should consist of 14 protons and 7 electrons, but it appears to have properties inconsistent with its being composed of an odd number of simple particles. However, very little is really known about nuclei, and the opinion is generally held by physicists that some way of evading this difficulty will be found and that all nuclei will ultimately be shown to be made up of electrons and protons. [中文](#)

It has always been the dream of philosophers to have all matter built up from one fundamental kind of particle, so that it is not altogether satisfactory to have two in our theory, the electron and the proton. There are, however, reasons for believing that the electron and proton are really not independent, but are just two manifestations of one elementary kind of particle. This connexion between the electron and proton is, in fact, rather forced upon us by general considerations about the symmetry between positive and negative electric charge, which symmetry prevents us from building up a theory of the negatively charged electrons without bringing in also the positively charged protons. Let us examine how this comes about. [中文](#)

The energy W of a particle in free space is determined in terms of its momentum p according to relativity theory by the equation

$$W^2/c^2 - p^2 - m^2c^2 = 0,$$

where m is the rest-mass of the particle and c is the velocity of light. This equation can easily be generalised to apply to a charged particle moving in an electromagnetic field and can be used as a Hamiltonian to give the equations of motion of the particle, and thus its possible tracks in space-time. [中文](#)

Now the above equation is quadratic in W , allowing of both positive and negative values for W . Thus for some of the tracks in space-time the energy W will have positive values and for the others negative values. Of course a particle with negative energy (kinetic energy is

referred to throughout) has no physical meaning. Such a particle would have less energy the faster it is moving and one would have to put energy into it to bring it to rest, quite contrary to anything that has ever been observed. [中文](#)

The usual way of getting over this difficulty is to say that the tracks for which W is negative do not correspond to anything real in Nature and are to be simply ignored. This is permissible only provided that for every track W is either always positive or always negative, so that one can tell definitely which tracks are to be ignored. This condition is fulfilled in the classical theory, where W must vary continuously, since W can never be numerically less than mc^2 and is thus precluded from changing from a positive to a negative value. In the quantum theory, however, discontinuous variations in a dynamical variable such as W are permissible, and detailed calculation shows that W certainly will make transitions from positive to negative values. We can now no longer ignore the states corresponding to a negative energy and it becomes imperative to find some physical meaning for them. [中文](#)

We can deal with these states mathematically, in spite of their being physically nonsense. We find that an electron with negative energy moves in an electromagnetic field in the same way as an ordinary electron with positive energy would move if its charge were reversed in sign, so as to be $+e$ instead of $-e$. This immediately suggests a connexion between negative-energy electrons and protons. One might be tempted at first sight to say that a negative-energy electron is a proton, but this, of course, will not do, since protons certainly do not have negative kinetic energy. We must therefore establish the connexion on a different basis. [中文](#)

For this purpose we must take into consideration another property of electrons, namely, the fact that they satisfy the exclusion principle of Pauli. According to this principle, it is impossible for two electrons ever to be in the same quantum state. Now the quantum theory allows

only a finite number of states for an electron in a given volume (if we put a restriction on the energy), so that if only one electron can go in each state, there is room for only a finite number of electrons in the given volume. We thus get the idea of a *saturated* distribution of electrons. 中文

Let us now make the assumption that almost all the states of negative energy for an electron are occupied, and thus the whole negative-energy domain is almost saturated with electrons. There will be a few unoccupied negative-energy states, which will be like holes in the otherwise saturated distribution. How would one of these holes appear to our observations? In the first place, to make the hole disappear, which we can do by filling it up with a negative-energy electron, we must put into it a negative amount of energy. Thus to the hole itself must be ascribed a positive energy. Again, the motion of the hole in an electromagnetic field will be the same as the motion of the electron that would fill up the hole, and this, as we have seen, is just the motion of an ordinary particle with a charge $+e$. These two facts make it reasonable to assert that *the hole is a proton*. 中文

In this way we see the proper role to be played by the negative-energy states. There is an almost saturated distribution of negative-energy electrons extending over the whole of space, but owing to its uniformity and regularity it is not directly perceptible to us. Only the small departures from perfect uniformity, brought about through some of the negative-energy states being unoccupied, are perceptible, and these appear to us like particles of positive energy and positive charge and are what we call protons. 中文

This theory of the proton involves certain difficulties, which will now be discussed. The theory postulates the existence everywhere of an infinite number of negative-energy electrons per unit volume, and thus an infinite density of electric charge. According to Maxwell's equations, this would give rise to an infinite electric field. We can

easily avoid this difficulty by a re-interpretation of Maxwell's equations. A perfect vacuum is now to be considered as a region in which all the states of negative energy and none of those of positive energy are occupied. The electron distribution in such a region must be assumed to produce no field, and only the departures from this vacuum distribution can produce a field according to Maxwell's equations. Thus, in the equation for the electric field E

$$\text{div } E = -4\pi\rho,$$

the electric density ρ must consist of a charge $-e$ for each state of positive energy that is occupied, together with a charge $+e$ for each state of negative energy that is unoccupied. This gives complete agreement with the usual ideas of the production of electric fields by electrons and protons. [中文](#)

A second difficulty is concerned with the possible transitions of an electron from a state of positive energy to one of negative energy, which transitions were the original cause of our having to give a physical meaning to the negative-energy states. These transitions are very much restricted when nearly all the negative-energy states are occupied, since an electron in a positive-energy state can then drop only into one of the unoccupied negative-energy states. Such a transition process would result in the simultaneous disappearance of an ordinary positive-energy electron and a hole, and would thus be interpreted as an electron and proton annihilating one another, their energy being emitted in the form of electromagnetic radiation. [中文](#)

There appears to be no reason why such processes should not actually occur somewhere in the world. They would be consistent with all the general laws of Nature, in particular with the law of conservation of electric charge. But they would have to occur only very seldom under ordinary conditions, as they have never been observed in the

laboratory. The frequency of occurrence of these processes according to theory has been calculated independently by several investigators, with neglect of the interaction between the electron and proton (that is, the Coulomb force between them). The calculations give a result much too large to be true. In fact, the order of magnitude is altogether wrong. The explanation of this discrepancy is not yet known. Possibly the neglect of the interaction is not justifiable, but it is difficult to see how it could cause such a very big error. [中文](#)

Another unsolved difficulty, perhaps connected with the previous one, is that of the masses. The theory, when one neglects interaction, requires the electron and proton to have the same mass, while experiment shows the mass ratio to be about 1,840. Perhaps when one takes interaction into account the theoretical masses will differ, but it is again difficult to see how one could get the large difference required by experiment. [中文](#)

An idea has recently been put forward by Oppenheimer (*Phys. Rev.*, vol. 35, p. 562) which does get over these difficulties, but only at the expense of the unitary theory of the nature of electrons and protons. Oppenheimer supposes that all, and not merely nearly all, of the states of negative energy are occupied, so that a positive-energy electron can never make a transition to a negative-energy state. There being now no holes which we can call protons, we must assume that protons are really independent particles. The proton will now itself have negative-energy states, which we must again assume to be all occupied. The independence of the electron and proton according to this view allows us to give them any masses we please, and further, there will be no mutual annihilation of electrons and protons. [中文](#)

At present it is too early to decide what the ultimate theory of the proton will be. One would like, if possible, to preserve the connexion between the proton and electron, in spite of the difficulties it leads to, as it accounts in a very satisfactory way for the fact that the electron

and proton have charges equal in magnitude and opposite in sign. Further advances in the theory of quantum electrodynamics will have to be made before one can deal accurately with the interaction and see whether it will settle the difficulties, or whether, perhaps, a new idea can be introduced which will answer this purpose. [中文](#)

(126, 605-606; 1930)

* Based on a paper read before Section A (Mathematical and Physical Science) of the British Association at Bristol on Sept. 8.

质子*

狄拉克

这篇文章报道了英国物理学家保罗·狄拉克就电子可能具有“负能量”从而带有正电荷这一预测所作的论述，该预测在更早些时候已发表在其他期刊上。狄拉克的“相对论性的”量子理论使量子力学与狭义相对论得以相容，前述的预测正是这一理论的结果。“带正电荷的电子”就像是无处不在的电子海中的“空穴”。狄拉克猜测，这些“带正电荷的电子”的行为方式与质子类似，不过这一猜测存在一些问题：质子与电子在质量上的差别非常大，而且据预测电子和这些空穴相遇会湮灭。在这里，狄拉克也提到了罗伯特·奥本海默的观点，即带正电荷的电子可能就是与电子的质量相同的另一种粒子。后来人们证明确实如此：这些粒子就是正电子，电子的反物质形式。

英文

物质是由原子构成的，每一个原子是由若干个围绕中心原子核转动的电子组成的。原子核很可能不是基本粒子，而是由电子和氢原子核（或者所谓质子）紧密束缚在一起构成的。这样所有的物质都只由这两种基本粒子构成，其中每一个电子带电荷 $-e$ ，每一个质子带电荷 $+e$ 。

英文

这里需要指出的是，氮原子的存在给这个观点提出了一个难题。由氮原子核的电荷和质量，我们可以推断出氮原子核是由14个质子和7个电子组成的，但是氮原子核表现出来的性质似乎与它是由奇数个基本粒子构成这一点不符。然而，关于原子核，我们知之甚少，而且物理学家们普遍认为将来总会有办法克服这个困难，并且最终将会证明所有的原子核都是由电子和质子构成的。

英文

哲学家总是梦想所有的物质都是由一种基本粒子构成的，所以我们

的理论——包含两种基本粒子（电子和质子）——并不能使所有人都满意。然而人们有理由相信电子和质子并不是毫无关系的，它们只是一种基本粒子的两种表现形式。而事实上，电子和质子之间的联系在某种程度上是关于正负电荷之间对称性的一般认识强加给我们的，这种对称性使我们不能构建一套只包含带负电的电子，而不包含带正电的质子的理论。下面让我们看看为什么会是这样。 [英文](#)

根据相对论，自由空间中粒子的能量 W 由它的动量 p 决定，即

$$W^2/c^2 - p^2 - m^2c^2 = 0,$$

其中 m 是粒子的静止质量， c 是光速。这个方程可以很容易地推广到带电粒子在电磁场中运动的情况，并且可以被用作哈密顿量，给出带电粒子的运动方程，从而得到带电粒子在时空中可能的径迹。 [英文](#)

上面的方程中 W 项是二次的，所以 W 既可能是正的，也可能是负的。因此对时空中的一些径迹而言能量 W 是正的，而对其他一些则是负的。当然粒子具有负能量（动能总是会涉及到）是没有物理意义的。这样的粒子运动得越快，它的能量就越小，我们不得不给它能量使它静止，然而这与我们观察到的所有现象都是截然不同的。 [英文](#)

通常克服这个困难的办法是认为具有负 W 的径迹不对应于任何真实的自然现象，而只需要简单地把它忽略掉。不过这只有在每一条径迹的 W 值恒正或者恒负的前提下才成立，因为只有这样我们才可以明确地判断哪一条径迹应该被忽略。这个条件在 W 连续变化的经典理论中是满足的，因为 W 在数值上不能小于 mc^2 ，所以排除了 W 从正值变化到负值的可能性。然而，在量子理论中，像 W 这样的动力学量可以不是连续变化的，并且详细的计算表明 W 确实可以从正值变化到负值。因此我们不能再忽略负能量对应的状态，而必须为它们寻找某种物理意义。 [英文](#)

我们可以从数学上处理这些状态，而先不去管它们是否具有物理意义。我们发现，如果普通电子的电荷符号发生翻转，即从 $-e$ 变为 $+e$ ，那么一个具有负能量的电子在电磁场中的运动方式和一个普通的具有正能量的正电子一样。这就意味着负能电子和质子之间存在某种联系。乍一看这种情况，人们可能会说负能电子就是质子，但是这无疑是不成立

的，因为质子的动能不可能是负的。因此，我们必须在另外的基础上构建它们的联系。 [英文](#)

为此我们必须考虑电子的另外一个特性，即它们满足泡利不相容原理。根据这一原理，两个电子永远不可能处于同一个量子态。因为量子理论在给定的空间内只允许有限数目的电子态（如果我们给能量一个限制），所以如果每一个态只允许一个电子占据，那么在给定的空间内只能容纳有限数目的电子。这样我们就会得到电子饱和分布的概念。

[英文](#)

现在我们假设电子的负能态几乎都被占据了，因此整个负能区域电子几乎是饱和的。有一些没被占据的负能态，它们就像饱和分布的负能态电子海中的一些空穴。在我们看来这些空穴是什么样的呢？首先，为了使这些空穴消失，我们需要填充一个负能量的电子，即放入一个负能量。这样空穴本身必须具有正能量。其次，空穴在电磁场中的运动方式和填充空穴的电子的运动方式一样，就像我们之前看到的那样，就是一个带 $+e$ 电荷的普通粒子的运动。这两个事实使我们有理由断言——空穴就是质子。 [英文](#)

这样我们就看到了负能态起到的作用。整个空间中负能电子几乎处于饱和分布，但由于它们表现出来的均匀性和规律性，因而不能直接被我们觉察到。只有在完美的均匀性上出现一些小的偏离，即有一些负能态没被占据，才能被我们觉察到。这些偏离在我们看来就是些具有正能量和带正电荷的粒子，也就是我们所谓的质子。 [英文](#)

这个关于质子的理论存在一些问题，下面我们就来讨论这些问题。这个理论假设空间每处单位体积内都存在无限数目的负能电子，这样电荷密度就是无穷大了。根据麦克斯韦方程，这将会产生一个无限大的电场。不过我们可以很容易地通过重新解释麦克斯韦方程来克服这个困难。理想的真空被认为是所有的负能态都被占据，而所有的正能态都没被占据的空间。我们认为在这样的空间中，电子分布不会产生任何场，只有当电子分布偏离真空分布时才会产生根据麦克斯韦方程得到的场。因此，在电场 E 的方程中

$$\operatorname{div} E = -4\pi \rho,$$

电荷密度 ρ 是由每一个被占据的正能态上的电荷 $-e$ 和每一个没被占据的负能态上的电荷 $+e$ 组成的。这和通常电子和质子产生电场的观点是完全一致的。 [英文](#)

第二个困难涉及到电子可能存在从正能态向负能态的跃迁，这种跃迁是我们必须赋予负能态以物理意义的最初原因。当几乎所有的负能态都被占据时，这种跃迁是非常受限制的，因为处于正能态的电子只能落入没被占据的负能态。这样的跃迁过程导致一个普通的正能态电子和一个空穴同时消失，所以可以解释成一个电子和一个质子的互相湮灭，它们的能量以电磁辐射的形式发射出来。 [英文](#)

看起来没有什么理由可以说明为什么这样的过程不能在现实世界的某处发生。它们会遵守自然界所有的一般规律，特别是电荷守恒定律。但是它们在普通条件下必然很少发生，因为即使在实验室中它们也还没有被观察到。一些研究者已经独立地计算出这些过程发生的理论频率，计算中忽略了电子和质子之间的相互作用（即它们之间的库仑力）。计算给出的结果太大了，肯定是不正确的。事实上，结果的数量级都是完全错误的。现在还不知道为什么会出现这样的差异。可能忽略相互作用是不合理的，但是仍然很难理解为什么会导导致这么大的错误。 [英文](#)

另外一个没有解决的困难就是质量问题，这可能和前一个困难有关。如果忽略相互作用，这个理论就要求电子和质子具有相同的质量，然而实验表明它们的质量比约为1,840。也许考虑相互作用后理论上的质量会有所不同，但还是很难理解怎样才能得到实验要求的那么大的质量差。 [英文](#)

奥本海默最近提出的一个观点（《物理学评论》，第35卷，第562页）的确可以解决这个困难，但是它却牺牲了关于电子和质子本质的统一理论。奥本海默假定所有的（不仅仅是几乎所有的）负能态都被占据了，因此正能电子不能跃迁到负能态。这里没有我们可以称之为质子的空穴，所以我们必须假定质子是真正独立的粒子。这样，质子本身也有自己的负能态，而且我们必须假设它们也被完全占据了。根据这个观点，电子和质子的独立性允许我们随心所欲地给它们的质量赋值，而且它们之间也不会相互湮灭。 [英文](#)

目前断定质子的最终理论还为时尚早。如果可能的话，人们愿意保留电子和质子之间的这种关系，而不管它带来的困难，因为它非常圆满地解释了这个事实——电子和质子携带的电荷大小相等，而符号相反。量子电动力学需要进一步的发展，人们才可以准确地计算相互作用，才可以知道我们的理论是否可以解决这些困难，或者是否会出现新的可以回答这个问题的观点。 英文

（王锋 翻译；李森 审稿）

* 基于9月8日在布里斯托尔向英国科学促进会的A分部（数学和物理科学）宣读的一篇论文。

The Ether and Relativity

J. H. Jeans

Here the English physicist James Hopwood Jeans responds to a letter from Oliver Lodge criticizing Jeans' recent claim that the laws of the universe would only be penetrated by the use of mathematics. Jeans affirms his belief that "No one except a mathematician need ever hope fully to understand those branches of science which try to unravel the fundamental nature of the universe—the theory of relativity, the theory of quanta and the wave mechanics." Lodge suggested that the universe might ultimately turn out to have been created or designed on aesthetic, rather than mathematical lines. If so, one might expect artists, not mathematicians, to be best suited to fundamental science. But Jeans notices no such aptitude in his artist friends. [中文](#)

I obviously must not ask for space to discuss all the points raised in Sir Oliver Lodge's interesting letter in *Nature* of Nov. 22, and so will attempt no reply to those parts of it which run counter to the ordinarily accepted theory of relativity. For I am sure nothing I could say would change his views here. But I am naturally distressed at his thinking I have quoted him with a "kind of unfairness", and should be much more so, had I not an absolutely clear conscience and, as I think, the facts on my side. [中文](#)

In the part of my book to which Sir Oliver objects most, I explained how the hard facts of experiment left no room for the old material

ether of the nineteenth century. (Sir Oliver explains in *Nature* that he, too, has abandoned this old material ether.) I then quoted Sir Oliver's own words to the effect that many people prefer to call the ether "space", and his sentence, "The term used does not matter much."

[中文](#)

I took these last words to mean, not merely that the ether by any other name would smell as sweet to Sir Oliver, but also that he thought that "space" was really a very suitable name for the new ether. He now explains he was willing to call the ether "space", "for the sake of peace and agreement". If I had thought it was only *qua* pacifist and not *qua* scientist that he was willing to call the ether "space", I naturally would not have quoted him as I did, and will, of course, if he wishes, delete the quotation from future editions of my book. But I did not know his reasons at the time, and so cannot feel that I acted unfairly in quoting his own words verbatim from an Encyclopaedia article. [中文](#)

Against this, I seem to find Sir Oliver attributing things to me that, to the best of my belief, I did not say at all, as, for example, that a mathematician alone can hope to understand the universe. My own words were (p. 128):

"No one except a mathematician need ever hope fully to understand those branches of science which try to unravel the fundamental nature of the universe—the theory of relativity, the theory of quanta and the wave-mechanics." [中文](#)

This I stick to, having had much experience of trying to explain these branches of science to non-mathematicians. In the same way, if the material universe had been created or designed on aesthetic lines—a possibility which others have contemplated besides Sir Oliver Lodge—then artists ought to be specially apt at these fundamental branches of science. I have noticed no such special aptitude on the part of my

artist friends. Incidentally, I think this answers the question propounded in the News and Views columns of *Nature* of Nov. 8, which was, in brief:—If the universe were fundamentally aesthetic, how could an aesthetic description of it possibly be given by the methods of physics? Surely the answer is that if the objective universe were fundamentally aesthetic in its design, physics (defined as the science which explores the fundamental nature of the objective universe) would be very different from what it actually is; it would be a *milieu* for artistic emotion and not for mathematical symbols. Of course, we may come to this yet, but if so, modern physics would seem rather to have lost the scent. [中文](#)

However, I am glad to be able to agree with much that Sir Oliver writes, including the quotations from Einstein which he seems to bring up as heavy artillery to give me the final *coup de grace*:—“In this sense, therefore, there exists an ether”, and so on. On this I would comment that nothing in science seems to exist any more in the good old-fashioned sense—that is, without qualifications; and modern physics always answers the question, “To be or not to be?” by some hesitation compromise, ambiguity, or evasion. All this, to my mind, gives strong support to my main thesis. [中文](#)

(126, 877; 1930)

J. H. Jeans: Cleveland Lodge, Dorking, Nov. 23.

以太与相对论

金斯

英国物理学家詹姆斯·霍普伍德·金斯写这篇文章是为了回应奥利弗·洛奇的一篇快报，奥利弗·洛奇在该快报文章中批评了金斯最近提出的观点，即宇宙中的定律只有用数学方法才能解释清楚。金斯坚持认为“除了数学家以外，没有人能完全理解那些试图揭示宇宙基本性质的科学分支——相对论、量子理论和波动力学。”洛奇认为宇宙的创造和设计最终有可能是按照美学原则而非数学原理进行的。如果事实真的如此，那么艺术家应该比数学家更适合研究基础科学。但金斯在他的艺术界朋友中没有发现这种特别的倾向。 [英文](#)

显然，我没有必要要求一个很大的版面来讨论奥利弗·洛奇爵士发表在11月22日《自然》上的那篇引人注目的快报中提到的全部要点，因而也不会试图回复该快报文章中那些与人们普遍接受的相对论不相符合的内容。因为我知道无论我在这里说什么也不能改变他的观点。但是，如果他认为我是以“一种不公正的方式”引述他的话，我自然会感到不安，而且，如果我不曾拥有一个绝对清晰的意识并认为事实一定站在我这一边的信念，我将会感到更加不安。 [英文](#)

在我的书中，奥利弗爵士最不赞同的部分是我关于铁一般的实验事实如何使得19世纪的旧的物质性以太再无容身之地的解释。（奥利弗爵士在《自然》上曾解释说他也已经抛弃了这种旧的物质性以太。）接着我引述了奥利弗爵士本人针对很多人更愿意称以太为“空间”这一现象所说的话，他的原话是，“用什么样的术语关系不大。” [英文](#)

我引用最后这句话是想说明，不仅以任何其他方式命名的以太一样合乎奥利弗爵士的胃口，而且他认为“空间”对于新的以太来说确实是一个很合适的名称。他现在解释说自己乐于称以太为“空间”，“为的是息事

宁人和意见统一”。如果我以前认为他只是作为和平主义者而不是作为科学家才乐于称以太为“空间”，自然就不会像我之前那样引述他的话，当然，如果他希望的话，我将在我那本书的新版中删去那段引文。但当时我并不知道他是这样想的，所以我不知道我从一篇百科全书的文章中一字不差地引述他的原话是不公正的做法。 [英文](#)

与此相反，我可以非常负责任地说，我发现奥利弗爵士把我根本没有说过的话强加在我身上，比如，单凭数学家就能理解宇宙。我的原话是这样的（第128页）：

“除了数学家以外，没有人能完全理解那些试图揭示宇宙基本性质的科学分支——相对论、量子理论和波动力学。” [英文](#)

我仍然坚持这一点，因为在试图向非数学家解释上述科学分支方面我已经积累了许多经验。同样地，如果物质性宇宙的创造和设计是按美学原则进行的——除了奥利弗·洛奇爵士之外还有其他人也曾考虑过这种可能性，那么艺术家应该特别容易理解这些基础的科学分支。迄今为止，在我的艺术家朋友中我并没有发现这种特别的倾向。顺便提一句，我认为这解答了11月8日《自然》的“新闻与视点”栏目中提出的问题，简单地说就是：如果宇宙基本上是美学的，那么物理学方法又怎么能给出一个关于宇宙的美学描述呢？答案只能是这样的，如果客观的宇宙基本上是依美学观点设计的，那么物理学（定义为研究客观宇宙基本性质的科学）将会与它实际的样子大为不同；这种依美学观点设计的宇宙环境将适合于艺术情感而非数学符号。当然，我们可以这样做，但是果真如此的话，现代物理学似乎会迷失方向。 [英文](#)

不过，我很高兴在很多方面与奥利弗爵士意见一致，包括他引用的爱因斯坦的话——“所以就这个意义而言，是有某种以太存在”等，看起来他要把这些当作重炮给我最终的致命一击。对此我的评论是，在科学中没有什么东西能以旧有的形式安然存在，这是绝对的；现代物理学经常会以某种迟疑不决的折衷、模棱两可或者遁辞来回答“存在还是不存在？”的问题。在我看来，所有这些都强有力地支持了我的主要观点。

[英文](#)

Unit of Atomic Weight

F. W. Aston

Francis Aston, working at the Cavendish Laboratory of the University of Cambridge, had devised an instrument for measuring the atomic masses of individual atoms, now called the mass spectrometer. This led him earlier to postulate the notion of isotopes, which have identical chemical properties but different masses. Having used the device to identify the isotopes of more than 80 different chemical elements, Aston here advocates the need for a new standard of atomic mass, to replace the practice then current of referring all masses to that of oxygen—for this element, having several isotopes, is not an appropriate reference point. [中文](#)

THE discovery of the complexity of oxygen clearly necessitates a reconsideration of the scale on which we express the weights of atoms. Owing to the occurrence of O^{17} and O^{18} , now generally accepted, it follows that the mean atomic weight of this element, the present chemical standard, is slightly greater than the weight of its main constituent O^{16} . The most recent estimate of the divergence is 1.25 parts per 10,000. [中文](#)

This quantity, even apart from its smallness, is not of much significance to chemists, for the experience of the last twelve years has shown that complex elements do not vary appreciably in their isotopic constitution in natural processes or in ordinary chemical operations. Physics, on the other hand, is concerned with the weights of the

individual atoms, and by the methods of the mass-spectrograph and the analysis of band spectra it is already possible to compare some of these with an accuracy of 1 in 10,000. Furthermore, the theoretical considerations of the structure of nuclei demand an accuracy of 1 in 100,000, which there is reasonable hope of attaining in the near future. The chemical unit is clearly unsuitable, and it seems highly desirable that a proper unit for expressing these quantities should be decided upon. [中文](#)

The proton, the neutral hydrogen atom, one-quarter of the neutral helium atom, one-sixteenth of the neutral oxygen atom 16, and several other possible units have been suggested. None of these is quite free from objection. It is desirable that this matter should be given attention, so that when a suitable opportunity occurs for a general discussion of the subject, each point of view may be afforded its proper weight in arriving at a conclusion. [中文](#)

(126, 953; 1930)

F. W. Aston: Trinity College, Cambridge, Dec. 4.

原子量的单位

阿斯顿

在剑桥大学卡文迪什实验室工作的弗朗西斯·阿斯顿设计了一种用来测量单个原子的原子质量的仪器，现在我们称之为质谱仪。这使得他更早地提出了同位素（化学性质完全相同但质量不同）的概念。利用该仪器鉴定了超过80种化学元素的同位素以后，在这篇文章中阿斯顿主张，有必要采用一种新的原子质量的标准，以取代当时测量所有其他原子质量时利用氧作为标准的做法——因为氧有多种同位素，不适合作为原子质量的参考标准。 [英文](#)

氧元素具有多种同位素，这一发现无疑使我们必须重新考虑用以表述原子量的标度。目前在化学上是以氧元素的平均原子质量作为原子量的标准，但由于现在同位素 O^{17} 和 O^{18} 的发现已经得到了普遍的认可，所以氧元素的平均原子质量略大于氧元素中的主要组成部分 O^{16} 的原子质量。最新的估计表明这一差别是0.125%。 [英文](#)

这个差值对于化学家来说没有太大的意义，更别说它还非常微小，因为最近12年的研究经验已经表明，对于同位素形式复杂多样的元素来说，在自然过程或者化学操作中其各种同位素的相对丰度并不发生明显改变。但是，物理学研究要考虑单个原子的质量，通过质谱仪和谱带分析的方法目前已经可以以万分之一的精度来分辨某些原子质量的差别。此外，对原子核结构的理论研究需要十万分之一的精度，在不久的将来对原子质量的测定有望能够达到这一精度。因此，目前化学上采用的原子量的单位显然是不合适的，对于物理学研究来说，似乎迫切需要确定一个能够描述这些量的合适的原子量单位。 [英文](#)

质子的质量，中性氢原子的质量，氢原子质量的 $1/4$ ，中性氧同位素 O^{16} 原子质量的 $1/16$ ，以及其他几种可能的原子量单位都被提出来

了。但所有这些无一例外都遭到了一些反对。这个问题应该受到关注，一旦出现一个对这一主题进行广泛讨论的合适时机，那么为了得出结论每一种观点都可以适当地发挥作用。 英文

（王锋 翻译；李芝芬 审稿）

Evidence for a Stellar Origin of the Cosmic Ultra-penetrating Radiation

V. F. Hess

Physicists were still pondering the nature of cosmic rays. Earlier studies failed to find any evidence that the Sun emitted such rays, but here Victor Hess reports new experiments showing that it does. As he notes, recent experiments at high altitude in the Swiss Alps found the average intensity of radiation to be higher during the day and lower at night. Further experiments with lead shielding showed that the Sun's light included a component of highly penetrating rays, with intensity equal to about 0.5 percent of the total observed cosmic ray intensity. Hess argues that cosmic rays most probably have a stellar origin, as all other stars probably emit them much as the Sun. The precise nature of these particles remained unknown. [中文](#)

WHILE in former years all observers were agreed that the sun does not contribute any noticeable amount to the total intensity of the cosmic ultra-radiation, the increase in the sensitivity of the apparatus used within recent years, and the increase in the number of observations made at different stations and under different experimental conditions, makes it possible to investigate once more whether the influence of the sun is altogether negligible. [中文](#)

Very accurate and trustworthy registrations of the cosmic radiation have been carried out with Prof. G. Hoffmann's high-pressure ionisation chamber at Muottas Muraigl (2,456 m. above sea-level) in the Engadine. These measurements show, beyond any doubt, that the average intensity of the radiation is somewhat greater in daytime than during the night. G. Hoffmann and F. Lindholm¹ give the average difference between day and night intensities as 0.12 mA., ~ 0.0125 ions per c.c. per sec. while the apparatus was unscreened from above, and 0.04 mA., $\sim 0.0042 I$ with a lead-screening of 6 cm. and 9 cm. thickness. (The letter "I" always denotes "ions per c.c. and sec.") F. Lindholm,² with the same apparatus, found from longer series of observations (8 months) the values in the accompanying table (see Table 6 of his paper). 中文

In Hoffmann and Lindholm's apparatus a compensation current of one milliamperere corresponds to an ionisation of 0.104 *I*. Therefore the total intensity of the ultra-radiation with the apparatus unscreened from above was about 2.50 *I* at Muottas Muraigl. 中文

The difference between day and night intensity can be taken, provisionally at least, as the actual intensity of the solar penetrating radiation. One can see at once that at Muottas Muraigl, 2,456 m. above sea-level, about one-half of this solar radiation component is able to penetrate through 10 cm. of lead. This component is therefore far more penetrating than the gamma rays from radioactive substances. If we assume that all of the above-mentioned 0.011 *I* is of solar origin, we can compute the absorption coefficient in lead μ_{Pb} (it will suffice to take the case of perpendicular incidence) from the equation $I = I_0 e^{-\mu_{Pb} d}$ taking $I_0 = 0.011$, $I = 0.0058$, and $d = 10$ cm.; thus we obtain $\mu_{Pb} = 0.064 \text{ cm.}^{-1}$ and the mass absorption coefficient $\left(\frac{\mu}{\rho}\right)_{Pb} = 5.7 \times 10^{-3} \text{ cm.}^2/\text{gm}$. 中文

This value is almost exactly equal to the mass absorption coefficient

value of the total cosmic radiation at the same altitude ($(\mu/\rho)_{Pb} = 6.3 \times 10^{-3} \text{ cm.}^2/\text{sec.}$ as found by Büttner on the Eiger glacier 2.3 km. above sea-level).³ If we assume that part of the (0.011 *I*) difference between day and night values with unscreened apparatus is due to an increase in the average content of radium emanation and its products in the air during daytime, then we should get an even more pronounced hardness of the solar penetrating rays, that is, a smaller value for their mass absorption coefficient. Therefore we are justified in concluding that *the sun emits penetrating rays of at least the same penetrating power as the well-known cosmic ultra-radiation. The total amount of the solar penetrating rays (at 2,456 m. above sea-level) is about one-half percent of the total intensity of the cosmic radiation, as it is seen from the accompanying table.* Of course, one might think it possible to explain the increase in the total radiation during daytime as due to an indirect influence of the sun (that is, an increase in the scattering of the ultra-rays by the heating of the atmosphere during the day). In this case, however, one would expect that this scattered radiation, represented by the difference between the day and night values, would be much softer than the general cosmic radiation; but this is in contradiction to the experimental results analysed above. 中文

Recent observations of R. Steinmaurer⁴ on the summit of the Sonnblick (3,100 m. above sea-level) in the summer of 1929, made with three different instruments (two of the Kolhörster double loop-electrometer type and one of the Wulf-Kolhörster type), also show clearly that the total ultra-radiation in daytime is slightly higher than at night; the difference amounts to about 0.7 percent (0.06 *I*, average difference for the three forms of apparatus mentioned above, the total intensity on the Sonnblick being about 8.7 *I* with the screening open on the top). The increase of radiation was also observed with apparatus screened with 7 cm. iron all around, but the number of these observations on the Sonnblick is not sufficient for quantitative calculations. It may be mentioned that even in the old observations on

the summit of the Obir (2,000 m. above sea-level), made by V. F. Hess and M. Kofler,⁵ the solar influence is noticeable (the total intensity of the ultra-radiation plus earth-radiation during the day being 11.11, during the night 11.09 *I*, in the average for 13 months), although at that time the apparatus were not screened from the earth radiation. The difference of 0.02 *I* was—at that time—considered as practically amounting to zero. 中文

Observations with apparatus of the Wulf- or Kolhörster type for shorter periods (like those of Kolhörster-v. Salis on the Jungfrauoch, on the Mönch, and of Büttner at other places in the Alps) naturally do not show the influence of the solar component of the ultra-rays, on account of the lesser degree of accuracy of the means; therefore Corlin,⁶ using the observations on the Mönch and the Zugspitze, came to negative conclusions as to the solar influence. From the data given below it is quite safe to conclude, according to the most accurate and most numerous observations at present available, that *the sun contributes an amount of about 0.5 percent to the total intensity of the cosmic ultra-radiation at 2.5 km. above sea-level. The penetrating power of the solar ultra-rays is at least as great as that of the total cosmic radiation.* There is no doubt that this solar component of the ultra-radiation is also present at lower levels; on account of its very small absolute intensity it will, of course, be far more difficult to prove its existence in these levels. An analysis of the very accurate registrations of the total radiation by Hoffmann and Steinke in Königsberg and in Halle in this direction might be successful. 中文

Period	Number of Days	Armour open above		
		Mean Values		Difference (Day-Night)
		Day	Night	
1928 January–March	(32)	24.46 mA.	24.34 mA.	0.12 mA. = 0.0125 <i>I</i>
1928 June, July, October	(39)	23.98 mA.	23.88 mA.	0.10 mA. = 0.0104 <i>I</i>
1929 January–February	(11)	24.68 mA.	24.59 mA.	0.09 mA. = 0.0094 <i>I</i>
Weighted average difference			0.011 <i>I</i>	

Period	Number of Days	Armour closed (10 cm. lead screening all around)		
		Mean Values		Difference (Day-Night)
		Day	Night	
1928 March	(2)	19.54 mA.	19.50 mA.	0.04 mA. = 0.0042 <i>I</i>
1928 July	(8)	19.21 mA.	19.17 mA.	0.04 mA. = 0.0042 <i>I</i>
1929 February	(6)	19.46 mA.	19.38 mA.	0.08 mA. = 0.0084 <i>I</i>
Weighted average difference behind 10 cm. lead			0.0058 <i>I</i> (ions/c.c./sec.)	

中文

If the sun, as the fixed star nearest to our planet, emits rays of about the same qualities as the total cosmic penetrating radiation, one cannot but assume that all fixed stars are sources of a radiation of similar qualities. The sun being a relatively old star of the yellow dwarf type may, of course, be expected to yield far less total quantity of the ultra-penetrating radiation than, for example, the younger giant stars. Naturally, the ultra-penetrating rays which we observe can only come from the outermost layers of the stars, since they are not able to penetrate material layers of more than a few hundred metres water equivalent.

中文

It is not possible, at present, to say more about the nature of these stellar ultra-rays: whether they are electrons or protons accelerated in cosmic electric fields, or indeed photons (quanta) created by atomic mass shrinking or annihilation processes. This hypothesis of a partly stellar origin of the ultra-penetrating cosmic radiation does not necessarily exclude the possibility that another part of this radiation is created in interstellar space by the formation of certain elements out of hydrogen, according to Eddington’s and Millikan’s ideas, although the principle of minimum hypothesis would rather induce us to try whether the stellar origin hypothesis, based on the experimental evidence of the solar ultra-penetrating rays, would suffice to explain

the observed facts. 中文

The conclusions put forward in this note certainly support the original ideas of Prof. Nernst first mentioned in 1921.⁷ A few years ago, when the first results of observations on the daily period according to sidereal time were published, he wished that it were possible to increase the sensitivity of our apparatus until we could detect the ultra-rays from a single stellar nebula or a single star. I think the results put forward here indicate that a modest beginning has been made in this direction. At least it has been possible now to detect the influence and the penetrating power of the ultra-rays from the sun. It may be added that the evidence here brought forward for a stellar origin of the cosmic ultra-rays is completely independent of the existence of a daily period according to sidereal time, a subject which is still under discussion. 中文

(127, 10-11; 1931)

Victor F. Hess: Institute of Experimental Physics, University of Graz, Austria, Nov. 4.

References:

1. *Gerlands Beitr. z. Geophysik*, **20**, 52 (1928).
2. *Gerlands Beitr. z. Geoph.*, **26**, 416-439 (1930).
3. *Zeitschr. f. Geophys.*, **3**, 179 (1927).
4. *Sitz. Ber. Akad. d. Wiss. Wien*, II. a. **139**, 281-318 (1930).
5. *Phys. Zeitschr.*, **18**, 585 (1917).
6. *Zeitschr. f. Physik*, **50**, 808-848 (1928).
7. *Das Weltgebäude im Lichte der neueren Forschung* (Verlag Springer, Berlin).

宇宙超穿透性辐射起源于恒星的证据

维克托·赫斯

物理学家们仍在思考宇宙射线的性质。以前的研究未能找到任何证据证明太阳发射了这类射线，如今维克托·赫斯报告了他用新的实验结果说明确实如此。正如他所指出的，在瑞士阿尔卑斯山上的高海拔区进行的一项最新实验发现，辐射的平均强度白天比晚上高。采用铅屏蔽板以后再做的实验表明，太阳光中包含一个穿透力很强的射线成分，其强度约为宇宙射线总观测强度的0.5%。赫斯认为宇宙射线很可能起源于恒星，因为除太阳以外所有其他恒星发射的宇宙射线很可能与太阳发射的一样多。这些粒子的确切性质现在还不清楚。

[英文](#)

在过去，所有的观测者一致认为，在宇宙超级辐射的总强度中，太阳没有任何值得注意的贡献。近年来，随着观测仪器灵敏度的不断增强，以及在不同国家、不同实验环境下进行的观测次数不断增多，于是有可能再一次研究由太阳造成的影响是不是可以完全忽略不计。

[英文](#)

有人把霍夫曼教授的高压电离室放在瑞士恩加丁地区的穆拉古尔山（海拔2,456 m）上，由此得到了一些非常准确而且可靠的有关宇宙辐射的数据。这些测量结果毫无疑问地说明白天的平均辐射强度要略高于夜晚。霍夫曼和林霍尔姆^[1]给出了昼夜间强度差异的平均值：当仪器上方没有屏蔽时，平均值为0.12 mA，或 ~ 0.0125 个离子每立方厘米每秒；当使用6 cm和9 cm厚的铅板屏蔽时，平均值是0.04 mA， ~ 0.0042 I（符号“*I*”通常表示“每立方厘米每秒的离子数”）。林霍尔姆^[2]使用同样的仪器进行了更长期的观测（8个月），所得数据列于附表中（参见

他文章中的表6)。

英文

在霍夫曼和林霍尔姆使用的仪器中，一个1 mA的补偿电流相当于0.104 I的电离值。由此得出，在穆拉古尔山上由顶部没有铅板屏蔽的仪器测得的超级辐射的总强度大约为2.50 I。

英文

我们至少可以暂时把昼夜间的强度差视为太阳贯穿辐射的实际强度。于是马上就可以看到在海拔2,456 m的穆拉古尔山上，大约有一半这类太阳辐射成分能够穿过10 cm厚的铅板。因此这部分辐射的穿透性大大高于放射性物质发出的 γ 射线。如果我们假设所有上述的0.011 I全部起源于太阳，我们就可以根据方程 $I = I_0 e^{-\mu_{pb} d}$ 计算出铅的吸收系数 μ_{pb} （只考虑垂直入射的情况已经足够），代入 $I_0 = 0.011$ ， $I = 0.0058$ 和 $d = 10$ cm，我们得到 $\mu_{pb} = 0.064$ cm⁻¹ 和质量吸收系数 $\left(\frac{\mu}{\rho}\right)_{Pb} = 5.7 \times 10^{-3}$ cm²/g。

英文

这个数值几乎精确地等于所有宇宙辐射在这个高度上的质量吸收系数（比特纳在海拔2.3 km的艾格尔冰川上的测量值为 $(\mu/\rho)_{Pb} = 6.3 \times 10^{-3}$ cm²/sec）。^[3]如果我们假设在没有屏蔽层的仪器上测量到的昼夜间差异（0.011 I）中，有一部分是由于白天空气中镭射气及其产物的平均含量上升引起的，那么我们观察到的太阳贯穿射线会更硬，即它们的质量吸收系数会更小。因此我们认为以下结论是合理的：太阳发出的贯穿射线的穿透能力至少与著名的宇宙超穿透辐射相当。太阳贯穿射线的总量（在海拔2,456 m处）大约占宇宙辐射总强度的0.5%，如附表所示。当然，有人可能将白天辐射总量的升高解释为受太阳间接影响所致（即白天被加热的大气增加了对超穿透射线的散射）。然而在这种情况下，因散射造成的辐射——由昼夜间辐射量的差异表示，会比一般的宇宙辐射更软；而这与上面分析的实验结果是矛盾的。

英文

1929年夏天，斯坦莫勒^[4]在松布利克山峰顶（海拔约3,100 m）用三种不同仪器（两台柯尔霍斯特型双环静电计和一台伍尔夫-柯尔霍斯特型）的最新观测也明确显示出测量的超级辐射总量白天的数值略高于夜晚；差值大约为0.7%（用上面提到的三种仪器测量的差值取平均后得到0.06 I，顶部没有屏蔽的仪器在松布利克山测量的总强度约为8.7 I。）当仪器四周用7 cm厚的铁板屏蔽时仍然可以观测到辐射量的增

加，但是在松布利克山上的观测次数太少不足以作出定量计算。人们也许会提到即使从之前赫斯和科夫勒^[5]在奥柏（海拔2,000 m）山顶的观测数据中也可以看出太阳带来的影响（超级辐射加上地球辐射的总强度在13个月中的平均值：白天为11.11 I，晚上为11.09 I），尽管那时的仪器没有屏蔽掉地球辐射的影响。0.02 I的差别在当时几乎可以被看作是零。

英文

至于使用伍尔夫型或柯尔霍斯特型仪器进行的短周期观测（比如冯萨利斯在少女峰和修士峰以及比特纳在阿尔卑斯山其他地方用柯尔霍斯特型仪器所做的观测），由于仪器精度不够高，自然也测不出太阳的超级射线成分的影响；因此科兰^[6]使用在修士峰和楚格峰上的观测结果得出太阳对辐射量无影响的结论。从下表的数据中完全可以得到以下结论，根据目前能得到的所有最精确的观测结果，我们认为在海拔2.5 km处，太阳辐射占宇宙超级辐射总强度的0.5%。太阳超能射线的穿透能力至少与宇宙辐射的总体穿透能力相当。毫无疑问，目前太阳的这一超穿透辐射成分的贡献仍然处于较低的水平。由于这一成分的绝对强度值很小，要想证实其存在非常困难，霍夫曼和施坦因克在柯尼斯堡和哈雷对总辐射量的非常精确的数据进行了分析，他们在这方面的努力也许会取得成功。

英文

周期	天数	上方防护外壳打开		
		平均值		差值（日一夜）
		日	夜	
1928 年 1~3 月	(32)	24.46 mA	24.34 mA	0.12 mA = 0.0125 I
1928 年 6、7、10 月	(39)	23.98 mA	23.88 mA	0.10 mA = 0.0104 I
1929 年 1~2 月	(11)	24.68 mA	24.59 mA	0.09 mA = 0.0094 I
加权平均差值：0.011 I				

周期	天数	防护外壳关闭（四周用 10 cm 厚铅板屏蔽）		
		平均值		差值（日一夜）
		日	夜	
1928 年 3 月	(2)	19.54 mA	19.50 mA	0.04 mA = 0.0042 I
1928 年 7 月	(8)	19.21 mA	19.17 mA	0.04 mA = 0.0042 I
1929 年 2 月	(6)	19.46 mA	19.38 mA	0.08 mA = 0.0084 I
用 10 cm 铅板屏蔽后的加权平均差值：0.0058 I（离子数 /c.c./ 秒）				

英文

作为离地球最近的恒星，如果太阳发出的射线具有与总的宇宙穿透性辐射大致相同的性质，则我们不得不假定所有恒星都是发出类似射线

的辐射源。太阳是一颗年代比较久远的黄矮星，它释放出的超级穿透性射线在总量上自然会远远少于那些年轻一些的巨星。当然，我们观察到的超级穿透性射线只能来自恒星的最外层，因为它们不可能穿过厚度超过几百米水当量的物质层。 [英文](#)

我们现在还不能对恒星超级射线的性质作更多的说明：不能判断它们到底是被宇宙电场加速的电子或质子，还是在原子质量减小或湮灭过程中放出的光子（量子）。按照爱丁顿和密立根的想法，虽然最小值原理假说更倾向于引导我们尝试用太阳超穿透性辐射为实验证据的恒星起源假说来解释全部观察到的现象，但是一部分超穿透性宇宙辐射源自恒星的假说未必非要排除另一部分宇宙辐射来自星际空间的可能性，星际空间中的宇宙辐射是在氢元素合成某些较重元素的过程中产生的。

[英文](#)

这篇短文中的结论理所当然地支持了能斯特教授在1921年时就已经率先提出的想法^[7]。几年前，当基于恒星时的日周期的首次观测结果发表出来时，他就希望能够提高仪器的灵敏度，直到我们能够分辨来自单个恒星或单一恒星星云的超级射线。我认为本文提供的结果可以表明朝这方面的努力已经开始。至少现在检测出太阳超级射线的影响力和穿透力已经成为可能。需要补充说明的是，这里提出的有关宇宙超级射线起源于恒星的证据完全独立于基于恒星时的日周期的存在，后者是一个仍在讨论之中的课题。 [英文](#)

（史春晖 翻译；马宇蓓 审稿）

Present Status of Theory and Experiment as to Atomic Disintegration and Atomic Synthesis*

R. A. Millikan

In the mid-1920s, Robert Millikan coined the term “cosmic rays” for the high-energy radiation recently detected in the upper atmosphere. While some physicists suggested that the rays might come from atmospheric electricity, Millikan favoured an extraterrestrial origin. Here he describes recent evidence supporting this view. The discovery of unstable radioactive elements showed that some process must have created these atoms in the relatively recent past by building heavier elements up out of lighter ones. Perhaps cosmic-ray collisions are the cause, Millikan suggests. He proposes a broader process of heavy-element formation in space, but today’s well-founded theory locates it in thermonuclear reactions within stars and supernovae, or during processes in the very early universe. [中文](#)

MY task is to attempt to trace the history of the development of scientific evidence bearing on the question of the origin and destiny of the physical elements. I shall list ten discoveries or developments, all made within the past hundred years, which touch in one way or another upon this problem and constitute indications or sign-posts on

the road toward an answer. [中文](#)

Prior to the middle of the nineteenth century, little experimental evidence of any sort had appeared, so that the problem was wholly in the hands of the philosopher and the theologian. Then came, first, the discovery of the equivalence of heat and work, and the consequent formulation of the principle of the conservation of energy, probably the most far-reaching physical principle ever developed. [中文](#)

Following this, and directly dependent upon it, came, second, the discovery, or formulation, of the second law of thermodynamics, which was first interpreted, and is still interpreted by some, as necessitating the ultimate “heat-death” of the universe and the final extinction of activity of all sorts; for all hot bodies are observed to be radiating away their heat, and this heat after having been so radiated away into space apparently cannot be reclaimed by man. This is classically and simply stated in the humpty-dumpty rhyme. As a natural if not necessary corollary to this was put forward by some, in entire accord with the demands of medieval theology, a *Deus ex machina* initially to wind up or start off this running-down universe.

[中文](#)

Then came, third, the discovery, through studies both in geology and biology, of the facts of evolution—facts which showed that, so far as the biological field is concerned, the process of creation, or upbringing from lower to higher forms, has been continuously going on for millions upon millions of years and is presumably going on now. This tended to direct attention away from the *Deus ex machina*, to identify the Creator with his universe, to strengthen the theological doctrine of immanence, which represents substantially the philosophic position of Leonardo da Vinci, Galileo, Newton, Francis Bacon, and most of the great minds of history down to Einstein. [中文](#)

Neither evolution nor evolutionists have in general been atheistic—

Darwin least of all—but their influence has undoubtedly been to raise doubts about the legitimacy of the dogma of the *Deus ex machina* and of the correlative one of the heat-death. This last dogma rests squarely on the assumption that we, infinitesimal mites on a speck of a world, know all about how the universe behaves in all its parts, or more specifically, that the radiation laws which seem to us to hold here cannot possibly have any exceptions anywhere, even though that is precisely the sort of sweeping generalisation that has led us physicists into error half a dozen times during the past thirty years, and also though we know quite well that conditions prevail outside our planet which we cannot here duplicate or even approach. Therefore the heat-death dogma has always been treated with reserve by the most thoughtful of scientific workers. No more crisp or more cogent statement of what seems to me to be the correct position of science in this regard has come to my attention than is found in the following recent utterance of Gilbert N. Lewis, namely, “Thermodynamics gives no support to the assumption that the universe is running down”. *“Gain of entropy always means loss of information and nothing more.”*

中文

The fourth discovery bearing on our theme was the discovery that the dogma of the immutable elements was definitely wrong. By the year 1900 the element radium had been isolated and the mean lifetime of its atoms found to be about two thousand years. This meant definitely that the radium atoms that are here now have been formed within about that time; and a year or two later the element helium was definitely observed to be growing out of radium here and now. This raised insistently the question as to whether the creation, or at least the formation, of all the elements out of something else may not be a continuous process—stupendous change in viewpoint the discovery of radioactivity brought about, and a wholesome lesson of modesty it taught to the physicist. But a couple of years later, uranium and thorium, the heaviest known elements, were definitely caught in the

act of begetting radium, and all the allied chain of disintegration products. Since, however, the lifetime of the parent atom, uranium, has now been found to be a billion years or so, we have apparently ceased to inquire whence it comes. We are disposed to assume, however, that it is not now being formed on earth. Indeed, we have good reason to believe that the whole radioactive process is confined to a very few, very heavy elements which are now giving up the energy which was once stored up in them—we know not how—so that radioactivity, though it seemed at first to be pointing away from the heat-death, has not at all, in the end, done so. Indeed, it seems to be merely one mechanism by which stored-up energy is being frittered away into apparently unreclaimable radiant heat—another case of humpty-dumpty. [中文](#)

The fifth significant discovery was the enormous lifetime of the earth—partly through radioactivity itself, which assigns at least a billion and a half years—and the still greater lifetime of the sun and stars—thousands of times longer than the periods through which they could possibly exist as suns if they were simply hot bodies cooling off. This meant that new and heretofore unknown sources of heat energy had to be found to keep the stars pouring out such enormous quantities of radiation for such ages upon ages. [中文](#)

The sixth discovery, and in many ways the most important of all, was the development of evidence for the interconvertibility of mass and energy. This came about in three ways. In 1901 Kaufman showed experimentally that the mass of an electron could be increased by increasing sufficiently its velocity: that is, energy could be definitely converted into mass. About the same time the pressure of radiation was experimentally established by Nichols and Hull at Dartmouth College, New Hampshire, and Lebedew at Moscow. This meant that radiation possesses the only distinguishing property of mass, the property by which we define it, namely, inertia. The fundamental

distinction between radiation and matter thus disappeared. These were direct, experimental discoveries. Next, in 1905, Einstein developed the interconvertibility of mass and energy as a necessary consequence of the special theory of relativity. If, then, the mass of the sun could in any way be converted into radiant heat, there would be an abundant source of energy to keep the sun going so long as necessary, and all our difficulties about the lifetimes of the sun and stars would have disappeared. But what could be the mechanism of this transformation? [中文](#)

Then came the seventh discovery, which constituted a very clear finger-post, pointing to the possibility of the existence of an integrating or building-up process among the physical elements, as well as in biological forms, in the discovery that the elements are all definitely built up out of hydrogen; for they—the ninety-two different atoms—were all found, beginning about 1913 by the new method of so-called positive ray analysis, to be exact multiples of the weight of hydrogen within very small limits of uncertainty. This fact alone raises very insistently the query as to whether they are not being built up somewhere out of hydrogen now. They certainly were once so put together, and some of them, the radioactive ones, are now actually caught in the act of splitting up. Is it not highly probable, so would say any observer, that the inverse process is going on somewhere, especially since the process would involve no violation either of the energy principle or of the second law of thermodynamics; for hydrogen, the element out of which they all must be built, has not a weight exactly one in terms of the other ninety-two, but about 1 percent more than one, so that since mass or weight had been found in the sixth discovery to be expressible in terms of energy, the union of any number of hydrogen atoms into any heavier element, meant that 1 percent of the total available potential energy had disappeared and was therefore available for appearance as heat. [中文](#)

When, about 1914–15, this fact was fitted by MacMillan, Harkins, and others into the demand made above in the fifth discovery for a new source of energy to keep the sun pouring out heat so copiously for such great lengths of time, is seemed to the whole world of physics that the building up of the heavier elements out of hydrogen under the conditions existing within the sun and stars had been practically definitely proved to be taking place. This would not provide an escape from the heat-death, but it would enormously postpone it, that is, until all the hydrogen in the universe had been converted into the heavier elements. [中文](#)

By this process, however, the suns could stoke at most but 1 percent of their total mass, assuming they were wholly hydrogen to begin with, into their furnaces, and 99 percent of the mass of the universe would remain as cold, dead ash when the fires were all gone out and the heat-death had come. But about 1917 the astronomer began to chafe under the time-limitation thus imposed upon him, and this introduced the eighth consideration bearing upon our theme. He could get a hundred times more time—from now on, much more than that, because only a small fraction of the matter in the universe is presumably now hydrogen—by assuming that, in the interior of heavy atoms, occasionally a negative electron gets tired of life at the pace it has to be lived in the electron world, and decides to end it all and commit suicide; but, being paired by Nature in electron-fate with a positive, he has to arrange a suicide pact with his mate, and so the two jump into each other's arms in the nucleus, and the two complementary electron lives are snuffed out at once; but not without the letting loose of a terrific death-yell, for the total mass of the two must be transformed into a powerful ether pulse which, by being absorbed in the surrounding matter, is supposed to keep up the mad, hot pace in the interiors of the suns. This discovery, or suggestion, to account for the huge estimated stellar lifetimes, of the complete annihilation of positive and negative electrons within the nucleus,

makes it unnecessary to assume, at least for stellar lifetime purposes, the building up of the heavier elements out of hydrogen. Indeed, it seems rather unlikely that both kinds of processes, atom-building and atom-annihilating, are going on together in the same spot under the same conditions, so we must turn to further experimental facts to get more light. [中文](#)

The ninth sign-post came into sight in 1927, when Aston made a most precise series of measurements on the relative masses of the atoms, which made it possible to subject to a new test the Einstein formula for the relation between mass and energy, namely, $E = Mc^2$. This Aston curve is one of the most illuminating finger-pointings we now have. It shows that:

1. Einstein's equation actually stands the quantitative test for radioactive or disintegrating processes right well, and therefore receives new experimental credentials.
2. The radioactive or disintegrating process with the emission of an alpha ray must be confined to a very few heavy elements, since these are the only ones so situated on the curve that mass can disappear, and hence heat energy appear, through such disintegration.
3. All the most common elements, except hydrogen, are already in their most stable condition, that is, their condition of minimum mass, so that if we disintegrate them we shall have to do work upon them, rather than get energy out of them.
4. Therefore, man's only possible source of energy other than the sun is the upbuilding of the common elements out of hydrogen or helium, or else the entire annihilation of positive and negative electrons; and there is no likelihood that either of these processes is a possibility on earth.
5. If the foregoing upbuilding process is going on anywhere, the least

penetrating and the most abundant radiation produced by it, that corresponding to the formation of helium out of hydrogen, ought to be about ten times as energetic as the hardest gamma rays, that is, it ought to correspond to about twenty-six million electron-volts in place of two and a half million.

6. Other radiations corresponding to the only other abundant elements, namely, oxygen (oxygen, nitrogen, carbon), silicon (magnesium, aluminium, silicon), and iron (iron group), should be found about four times, seven times, and fourteen times as energetic as the “helium rays”.

7. The radiation corresponding to the smallest annihilation process that can take place—the suicide of a positive and negative electron—is three hundred and fifty times as energetic as the hardest gamma ray, or thirty-five times as energetic as the “helium ray”. [中文](#)

This brings us to the tenth discovery, that of the cosmic rays. These reveal:[†](#)

1. A radiation, the chief component of which, according to our direct comparison, is five times as penetrating as the hardest gamma ray, which, with the best theoretical formula we have relating energy and penetrating power (Klein–Nishina), means a ray ten times as energetic as the hardest gamma ray, *precisely according to prediction*.

2. Special bands of cosmic radiation that are roughly where they should be to be due to the formation of the foregoing abundant elements out of hydrogen, though (for reasons to be given presently) no precise quantitative check is to expected except in the case of helium.

3. No radiation of significant amount anywhere near where it is to be expected from the annihilation hypothesis, thus indicating that at least 95 percent of the observed cosmic rays are due to some other less

energetic processes.

4. A radiation that is completely independent of the sun, the great hot mass just off our bows, and not appreciably dependent on the Milky Way or the nearest spiral nebula, Andromeda, one that comes in to us practically uniformly from all portions of the celestial dome, and is so invariable with both time and latitude at a given elevation that the observed small fluctuations at a given station reflect with much fidelity merely the changes in the thickness of the absorbing air blanket through which the rays have had to pass to get to the observer. [中文](#)

This last property is the most amazing and the most significant property exhibited by the cosmic rays, and before drawing the final conclusions its significance will be discussed. For it means that at the time these rays enter the earth's atmosphere, they are practically pure ether waves or photons. If they were high-speed electrons or even had been appreciably transformed by Compton encounters in passing through matter into such high-speed electrons or beta rays, these electrons would of necessity spiral about the lines of force of the earth's magnetic field and thus enter the earth more abundantly near the earth's magnetic poles than in lower latitudes. This is precisely what the experiments made during the last summer at Churchill, Manitoba (lat. 59° N.), within 730 miles of the north magnetic pole, showed to be *not true*, the mean intensity of the rays there being not measurably different from that at Pasadena in lat. 34° N. [中文](#)

Nor is the conclusion that the cosmic rays enter the earth's atmosphere as a practically pure photon beam dependent upon these measurements of last summer alone. It follows also from the high altitude sounding-balloon experiments of Millikan and Bowen in April 1922, taken in connexion with the lower balloon flights of Hess and Kolhörster in 1911–14. For in going to an altitude of 15.5 km. we got but one-fourth the total discharge of our electroscope which we

computed we should have obtained from the extrapolation of our predecessors' curves. This shows that somewhere in the atmosphere below a height of 15.5 km. the intensity of the ionisation within a closed vessel exposed to the rays goes through a maximum, and then decreases, quite rapidly, too, in going to greater heights. We have just taken very accurate observations up to the elevation of the top of Pike's Peak (4.3 km.), and found that within this range the rate of increase with altitude is quite as large as that found in the Hess and Kolhörster balloon flights, so that there can be no uncertainty at all about the existence of this maximum. Such a maximum, however, means that the rays, before entering the atmosphere, have not passed through enough matter to begin to get into equilibrium with their secondaries—beta rays and photons of reduced frequency—in other words, *that they have not come through an appreciable amount of matter in getting from their place of origin to the earth.* 中文

This checks with the lack of effect of the earth's magnetic field on the intensity of the rays; and the two phenomena, of quite unrelated kinds and brought to light years apart, when taken together, prove most conclusively, I think, that the cosmic rays cannot originate even in the outer atmospheres of the stars, though these are full of hydrogen and helium in a high temperature state, but that they must originate rather in those portions of the universe from which they can come to the earth without traversing matter in quantity that is appreciable even as compared with the thickness of the earth's atmosphere—in other words, *that they must originate in the intensely cold regions in the depths of interstellar space.* 中文

Further, the more penetrating the beta rays produced by Compton encounters, the greater the thickness of matter that must be traversed before the beam of pure photons which enters the atmosphere gets into equilibrium with its secondaries; and until such equilibrium is reached, the apparent absorption coefficient must be less than the

coefficient computed with the aid of the Klein–Nishina formula from the energy released in the process from which the radiation arises. Now the Bothe–Kolhörster experiments of about a year ago show that when the energies of the incident photons are sufficiently high, the beta rays released by Compton encounters do indeed become abnormally penetrating: so that it is to be expected that, for the cosmic rays produced by the formation of the heavier of the common elements like silicon and iron out of hydrogen, the observed absorption coefficients will be somewhat smaller than those computed from the energy available for their formation. This is precisely the behaviour which our cosmic ray depth-ionisation curve actually reveals. At the highest altitudes at which we have recently observed (14,000 ft.), the helium rays have reached equilibrium with their secondaries, and the observed and computed coefficients agree as they should. For the oxygen rays the observed coefficient is a little lower than the computed value—about 17 percent lower; for the silicon rays still lower—about 30 percent; and for the iron rays considerably lower still—about 60 percent: all in beautiful qualitative agreement with the theoretical demands as outlined. [中文](#)

The foregoing results seem to point with much definiteness to the following conclusions:

1. The cosmic rays have their origin not in the stars but rather in interstellar space.
2. They are due to the building up in the depths of space of the commoner heavy elements out of hydrogen, which the spectroscopy of the heavens shows to be widely distributed through space. That helium and the common elements oxygen, nitrogen, carbon, and even sulphur, are also found between the stars is proved by Bowen's beautiful recent discovery that the "nebulium lines" arise from these very elements.

3. These atom-building processes cannot take place under the conditions of temperature and pressure existing in the sun and stars, the heats of these bodies having to be maintained presumably by the atom-annihilating process postulated by Jeans and Eddington as taking place there.

4. All this says nothing at all about the second law of thermodynamics or the *Wärme-Tod*, but it does contain a bare suggestion that if atom formation out of hydrogen is taking place all through space, as it seems to be doing, it may be that the hydrogen is somehow being replenished there, too, from the only form of energy that we know to be all the time leaking out from the stars to interstellar space, namely, radiant energy. This has been speculatively suggested many times before, in order to allow the Creator to be continually on his job. Here is, perhaps, a little bit of *experimental* finger-pointing in that direction. But it is not at all proved or even perhaps necessarily suggested. If Sir James Jeans prefers to hold one view and I another on this question, no one can say us nay. The one thing of which we may all be quite sure is that neither of us *knows* about it. But for the continuous building up of the common elements out of hydrogen in the depths of interstellar space the cosmic rays furnish excellent experimental evidence. I am not unaware of the difficulties of finding an altogether satisfactory kinetic picture of how these events take place, but acceptable and demonstrable facts do not, in this twentieth century, seem to be disposed to wait on suitable mechanical pictures. Indeed, has not modern physics thrown the purely mechanistic view of the universe root and branch out of its house? 中文

(127, 167-170; 1931)

Robert A. Millikan: California Institute of Technology, Pasadena, California.

* Retiring presidential address to the American Association for the Advancement of Science, delivered at Cleveland on Dec. 29.

† See articles by Millikan and by Millikan and Cameron, *Phys. Rev.*, Dec. 1, 1930, and in press.

原子衰变与原子合成的理论和实验 现状*

罗伯特·密立根

20世纪20年代中期，罗伯特·密立根将最新在高层大气中发现的高能辐射命名为“宇宙射线”。虽然有些物理学家认为这种射线可能来自大气电，而密立根则赞成其起源于地球之外。他在这篇文章中介绍了近期得到的一些证据以支持这一观点。不稳定放射性元素的发现说明：在不久以前，一定有某种轻元素合成重元素的过程产生了这些原子。密立根认为宇宙射线的碰撞可能就是起因。他还提出了较为广泛地在宇宙空间中形成重元素的过程，但当今确立的理论则认为重元素的生成过程起源于恒星和超新星内部的热核反应，或者形成于早期宇宙的某些反应之中。 [英文](#)

我的任务是试图追溯关于物质元素起源和命运问题的科学证据的发展历史。我将列出10个最近100年内的发现或进展，它们会以这种或那种方式与此问题相关联，并且充当着通向答案之路上的指示灯或者路标。 [英文](#)

在19世纪中叶以前，人们几乎得不到任何实验上的证据，所以这个问题的解答完全由哲学家和神学家说了算。然后出现了第一个发现，即热和功的等价性，由此导致了能量守恒定律，后者或许能称得上是迄今为止影响最为深远的物理定律。 [英文](#)

在这之后，并与此直接相关，热力学第二定律作为第二个发现或构想出现了，该定律最初被解释为（某些人至今仍作此解释）宇宙必然要走向最终的“热寂”，各种活动最终都将停止；因为人们发现所有热的物体都在向外辐射自己的热量，以这种方式散发到宇宙中去的热量显然无

法被人类收回。这和经典而简单的《汉普蒂·邓普蒂》歌谣中描述的情况相符（译者注：humpty-dumpty在歌谣中被比作“一经损坏就无法修复的东西”）。有些人提出这即使不是必然结果也是一种很自然的结果，完全适合了中世纪神学的要求，即最初是由救世主灭世或创世这个不断被耗尽的宇宙的。 [英文](#)

然后出现了第三个发现，地质学和生物学对进化现象的研究结果表明：就生物学领域而言，创造生命的过程或从低级形式向高级形式发展的过程，已经持续了亿万年而且据推测现在还在继续。这似乎使人们的视线从救世主中转移开来，认为造物主与他的天地万物是等同的，从而强化了上帝无所不在的神学理论，这一理论充分反映了历史上大多数伟大的思想家，从列奥纳多·达·芬奇、伽利略、牛顿、弗朗西斯·培根，一直到爱因斯坦的哲学立场。 [英文](#)

一般而言，进化论和进化论者都不倾向于无神论——达尔文尤其如此——但是由于他们的影响，人们的确已开始怀疑救世主理论以及与之相联系的热寂说的合理性。这个最后的学说直接需要假设，我们人类，这些宇宙中某一点上的无限小微粒，已经了解了宇宙中所有组成部分的行为，或者更明确地说，我们现在认定的辐射定律不可能在任何地方出现例外情况，尽管它就是那个曾让我们这些物理学家在过去的30年里犯过6次错误的并非普适的定律，也尽管我们很清楚地知道我们所在行星之外的环境是我们无法复制甚至是无法介入的。因此，大多数有思想的科学工作者都对热寂说采取保留的态度。在我所注意到的关于该问题的正确科学观点方面，没有谁的观点比吉尔伯特·刘易斯在最近讲话中的下述论断更简明、更有说服力，即“热力学并不支持宇宙在退化的假设”。“熵的增加通常只意味着信息的减少，仅此而已”。 [英文](#)

第四个与我们这个主题相关的发现是，元素不可改变的观点是完全错误的。到1900年，元素镭已经被分离出来，并得出镭原子的平均寿命大约为2,000年。这显然说明现在的镭原子大约是在那个时间范围内形成的；一两年以后，人们可以观测到从镭中生成的氦元素。这使人们急切地想知道，所有这些由其他元素生成新元素的创造过程，或至少可以说是形成过程，是否不会连续进行——放射性的发现带来了观念上的巨大变化，也有益地告诫了物理学家们要谦虚。然而几年之后，目前已知

的两种最重的元素——铀和钍，已被确认都能在生成镭以及一系列相关的衰变产物的过程中得到。既然现在发现作为母原子铀的寿命在10亿年左右，显然我们不用再去追问它是从哪儿来的了。然而，我们倾向于假定它不是现在在地球上形成的。实际上，我们有足够的理由相信所有的放射性过程只局限于极少数很重的元素，它们目前正在释放曾经储存在其内部的能量——我们不知道这种储存是怎样实现的——所以虽然放射现象起初似乎远离了热寂说，可到了最后却不是完全如此。放射现象看起来其实仅仅是储存能慢慢转化为明显不可逆转的辐射热的一种机制——“汉普蒂·邓普蒂”的另一个实例。 [英文](#)

第五个重大发现是发现地球已经存在了很长时间——部分是根据元素放射性确定的，地球年龄至少为15亿年，而太阳和其他恒星的年龄则更长——这个年龄要比假设恒星作为一个炽热的天体仅是单纯地不断冷却所耗的时间长几千倍。这意味着我们不得不去寻找能使恒星在漫长岁月里不断释放出大量辐射的热能的新来源，这种能源迄今为止尚不可知。 [英文](#)

第六个发现是找到了质量和能量相互转化的证据，从许多方面来看，这个发现是所有发现中最重要的。这可以从三方面说明。1901年考夫曼用实验证明，通过充分提高电子的速度可以增加电子的质量：也就是说，能量确实可以转化为质量。几乎是同时，新罕布什尔州达特茅斯学院的尼科尔斯、赫尔和莫斯科的列别捷夫用实验验证了辐射压的存在。这说明辐射具有质量的唯一与众不同的特征，即惯性。这样辐射和物质之间的根本区别就消失了。这些都是直接由实验发现的。紧接着在1905年，爱因斯坦利用狭义相对论推导出质量和能量之间的相互转化这一必然结果。假如太阳的质量可以通过某种方式转化为辐射热，那么就有了充足的能量来源以保持太阳在如此长的时间里放出热，而我们对太阳及其他恒星年龄的疑问也就不复存在了。但是这种转变机制又是什么呢？ [英文](#)

于是就有了第七个发现，这个发现非常明确地指出：组成物质的元素之间有可能出现积聚或合成的过程，在生物形态中也是如此，人们发现元素无疑都是由氢元素构成的；因为自1913年以来用所谓的阳射线分析法发现：92种不同原子的重量均为氢元素重量的精确倍数且误差极

小。仅仅是这一事实就使人们迫切想知道它们是不是现在正在某个地方由氢合成。它们肯定曾被这样合成过，而且现在它们之中的那些放射性元素会在裂变的过程中被发现。任何观测者都会说，很有可能在某处正进行着裂变的逆过程，特别是当这个过程并不违反能量原理和热力学第二定律的时候。氢作为构建其他元素的必要成分，相对于其他92个元素来说，其重量并不正好是1，而是比1大1%。所以既然在第六个发现中质量或重量可以表现为能量的形式，则任意数目的氢原子合并成任何较重元素时意味着全部可利用势能的1%消失了，并转化成了可以释放的热能。 [英文](#)

大约在1914至1915年，这个事实被麦克米伦、哈金斯等人用作解释第五个发现中所需的一种新能源，以保持太阳长期散发出巨大的热量。对整个物理学界来说，由氢构成更重元素的过程实际上已被证明在太阳和恒星内部环境下确实在发生。这并不能使宇宙摆脱热寂的结局，但可以极大地推迟它的到来，也就是说，可以推迟到宇宙中所有的氢都被转化成了较重的元素时才发生。 [英文](#)

然而，假设这些像太阳一样的恒星全部由氢元素构成，并将它们投入其自身的熔炉之中，这一过程最多只能消耗掉其总质量的1%，宇宙中99%的质量在燃料烧尽热寂来临时将变为冰冷的死灰。但在1917年前后，天文学家开始对这个强加给他的时间限制感到烦扰，并由此引出了与我们这个主题相关的第八个设想。他从现在起可以获得比那个时间限制长几百倍甚至更长的时间，因为据推测现在宇宙中的物质只有一小部分是氢——假设在重原子内部，偶尔一个负电子对自己不得不生活在电子世界中感到厌倦而决定通过自杀结束这一切；但自然界注定电子要和正电子配成对，它必须筹划与自己的搭档一起自杀，这样在原子核中它们两个分别跳到了对方的怀抱中，这两个正负互补的电子的生命同时结束；但在死亡时并非没有发出临死前那可怕的叫喊，因为它们两个的总质量必然转化成一个强大的以太脉冲，并被周围物质吸收，该过程被认为是保持恒星内部剧烈热反应的原因。这个发现或提议，即利用原子核内部正负电子的彻底湮灭来解决预测的恒星年龄大得不可思议的难题，使人们至少在恒星年龄问题上不需要假设由氢合成重元素的过程。的确，原子合成和原子湮灭这两类过程在同一地点同一条件下同时进行看

起来不太可能，所以我们必须通过更多的实验得到更清楚的解释。

英文

1927年，当阿斯顿对原子的相对质量进行了一系列非常精确的测定，使爱因斯坦在质量和能量之间建立的公式，即 $E = Mc^2$ 得到了新的验证之后，第九个里程碑也就出现在了人们的视野中。阿斯顿曲线是我们目前拥有的最具启发性的指证之一。它说明了以下几点：

1. 爱因斯坦方程实际上可用作放射性或衰变过程的有效的定量检验，因而增加了实验的可信度。

2. 放出一个 α 射线的放射性或衰变过程肯定只局限于很少几个重元素之中，因为它们在曲线中处于质量可能减少的位置上，因而可以通过这样的衰变过程释放出热能。

3. 所有除氢以外的最常见的元素都处于最稳定的状态之中，也就是说，它们处于质量最小的状态，所以如果我们想让它们发生衰变必须对它们做功，而不是从中获取能量。

4. 因此，除了太阳以外，人类可能获得能量的方式只有通过用氢或氦合成普通元素，或正负电子全部湮灭的过程；这两个过程都不可能在地球上发生。

5. 假如上述合成过程可以在任意地点进行，由此产生的穿透力最弱、强度最高的辐射，按照由氢合成氦的过程推算，应该能够达到最硬的 γ 射线能量的10倍左右，也就是说，大致相当于26百万电子伏特而不是2.5百万电子伏特。

6. 与其他含量丰富的元素，即氧（氧、氮、碳），硅（镁、铝、硅）和铁（铁族元素）相关联的辐射过程所对应的能量应当分别约为“氦射线”的4倍、7倍和14倍。

7. 由可能发生的最小的湮灭过程——正负电子的自杀过程发出的辐射是最硬的 γ 射线能量的350倍，是“氦射线”能量的35倍。

英文

这把我们引入了与宇宙射线相关的第十个发现。观测表明†：

1. 我们根据直接对比发现：一个主体部分是穿透力为最硬的 γ 射线5倍的辐射，用能量与穿透力之间最好的理论公式——克莱因-仁科公式计算，该射线的能量为最硬的 γ 射线的10倍，这是根据预测推算的精确结果。

2. 宇宙辐射的特殊频带，大致位于由氢合成上述含量丰富元素时产生的辐射应在的位置，尽管（由于马上要提到的原因）除了氦元素以外，我们都不能进行精确的定量计算。

3. 在正负电子湮灭假设对应的位置附近没有观测到数量显著的辐射，这说明观测到的宇宙射线至少有95%是由其他一些能量较低的过程造成的。

4. 这种辐射与就在我们凸窗外面的那个巨大的发热体，即太阳完全不相干，而且与银河系或离我们最近的旋涡星云——仙女座星云也没有关系，它几乎均匀地从天穹的各个位置向我们而来，在某一特定的高度，其观测值不随时间和纬度而变，个别观测站观测值的微小涨落仅仅是由于射线在到达观测器之前必须要穿过的大气吸收层的厚度变化造成的，这种涨落是吸收层厚度变化的真实反映。 [英文](#)

最后一个特性是宇宙射线最令人惊异也是最重要的特性，在下最终定论之前将对这个问题的重要性进行讨论。因为这意味着宇宙射线在进入地球大气层时基本上是由纯以太波或光子组成的。如果它们是高速运动的电子，或曾经在穿透物质的过程中因发生康普顿碰撞而转化成了高速电子或 β 射线，那么这些电子必然是以围绕地球磁力线的螺旋形轨迹前进的，因此进入地球两磁极的射线应该比低纬度地区的多。但去年夏天在距离北磁极730英里的马尼托巴省丘吉尔市（北纬59°）进行的实验说明事实并非如此，在那里测量的射线平均强度值与在北纬34°的帕萨迪纳得到的测量值没有什么区别。 [英文](#)

进入地球大气层的宇宙射线几乎全部由光子组成这一结论并不仅仅是根据去年夏季的测量结果，它也能从1922年4月密立根和鲍恩利用探空气球在高空处进行的实验和与之相关联的赫斯和柯尔霍斯特1911~1914年低空区的气球实验中找到根据。因为在到达15.5千米的高度时，验电器的放电量并没有达到我们根据前人实验曲线外推得到的计算值，

而仅为它的四分之一。这说明在大气中某个低于15.5千米的地方，密闭容器内宇宙射线导致的电离程度先是达到了一个最大值，但当升至更高的高度后又开始急剧下降。我们刚刚对派克峰（4.3千米）峰顶以下各个高度处的射线强度进行了精确的测量，发现在这个范围内，射线强度随高度上升的增加率与赫斯和柯尔霍斯特在气球飞行实验中得到的结果一致，所以存在一个最大值是毋庸置疑的。但这个最大值说明宇宙射线在到达地球大气层之前并没有穿过足够厚的物体以能与它们的次级粒子—— β 射线和频率降低的光子达到平衡。也就是说，这些射线在从它们的发源地到地球之间未曾穿过数量可观的物质。 [英文](#)

这证实了地球磁场对宇宙射线强度没有影响；这两个现象完全不相干，并且相距若干光年，当把它们联系在一起的时候，我认为可以下结论说：宇宙射线不可能发源于恒星，哪怕是在它的大气外层，尽管那里有大量处于高温中的氢和氦。不过它们肯定是来自宇宙中那些能让它们甚至不必穿透和地球大气层一般厚的物质就可以到达地球的地方——换句话说，宇宙射线必定起源于星际空间深处的超低温区域。 [英文](#)

此外，由康普顿碰撞产生的 β 射线的穿透力越强，进入大气层的纯光子束在与它的次级粒子达到平衡之前需要穿透的物质厚度就越大；且当达到此种平衡时，测得的表现吸收系数肯定小于根据辐射产生过程中释放的能量通过克莱因-仁科公式计算得到的系数。因为一年前的博思-柯尔霍斯特实验证明，当入射光子的能量足够高的时候，由康普顿碰撞产生的 β 射线确实表现出格外强的穿透力；所以可以预测，如果宇宙射线是在由氢合成像硅和铁这样较重的常见元素时产生的，则所观察到的吸收系数将比根据合成过程可获得的能量计算得到的系数低一些。这正是我们的宇宙射线深度-电离曲线揭示出来的特性。在我们最近测量的最大高度处（14,000英尺），氦射线已经和它们的次级粒子达到了平衡，因而系数测量值和计算值达到了应有的一致。对于氧射线，系数测量值略低于计算值——约低17%；硅射线更低一些——约30%；而铁射线则低得更多——约60%；但它们都与所述的理论要求定性地一致。

[英文](#)

根据上述结果显然可以得到以下结论：

1. 宇宙射线的发源地不是恒星，而是在星际空间。

2. 宇宙射线起源于太空深处的氢合成较为常见的重元素的过程，太空的光谱表明这些重元素广泛地分布于宇宙中。鲍恩的最新发现证明氢和常见元素氧、氮、碳甚至硫都存在于恒星间的太空中，这个出色的发现即“**氦线**”就是由这些元素引起的。

3. 这样的原子合成过程不可能在太阳或其他恒星内的高温高压环境下进行，根据金斯和爱丁顿的设想，这些天体的热量也许只能靠发生在那里的原子湮灭过程来维持。

4. 所有这些都未提及热力学第二定律或热寂，但它确实包含了这样一个假设：假如由氢合成其他原子的过程在宇宙空间中普遍存在，就像我们现在看到的这样，那么氢元素有可能也在同一地点以某种方式得到补充，即通过我们已知的从恒星向星际空间不断释放能量的唯一方式——辐射能。为了使造物主的工作得以延续下去，这一点以前已经被设想过多次了。在这方面也许有一点点实验上的迹象。但它根本就得不到验证，甚至可能连提出的必要都没有。如果在这个问题上詹姆斯·金斯爵士支持一个论点而我倾向于另一个，没有人能说我们不对。也许只有一件事情我们能完全确定，那就是我们俩对此都一无所知。不过宇宙射线就可以很好地为在广袤星际空间中存在由氢不断合成常见元素的过程提供实验上的证据。我不是不知道要找到一个完全令人满意的动力学解释来说明这些现象的来龙去脉是困难的，但是在20世纪，可接受的明显事实似乎无意于长期等候合适的机械性理论解释的出现。事实上，当代物理学不是已经彻底把纯粹机械的宇宙观赶出门外了吗？ **英文**

（王锋 翻译；朱永生 审稿）

* 卸任美国科学促进会会长的演说辞，12月29日发表于克利夫兰市。

† 见密立根以及密立根和卡梅伦发表在《物理学评论》上的文章，1930年12月1日，即将出版。

New Aspects of Radioactivity*

C. D. Ellis

With the quantum theory of atomic structure in place, physicists began to ponder the structure of the nucleus. Observations of high-energy electromagnetic radiation called gamma rays emitted by radioactive nuclei seemed to offer information on internal nuclear states. Here Charles D. Ellis discusses several of the most promising techniques for investigating these gamma rays. The most useful involved measuring the energies of secondary electrons ejected from an atom by the photoelectric effect, involving fine wires coated with an atomically thin layer of radioactive material. Although the gamma ray energies could only be measured to an accuracy of one part in 500, Ellis is hopeful that such data will clarify nuclear structure in the near future. 中文

γ -ray and Nuclear Structure

UNTIL a few years ago, the fundamental problems of physics were those concerned with the structure of the atom. The nucleus was necessarily often referred to, but only in relation to its effect on the behaviour of the electrons in the atom. It was found that for most purposes the net charge, Ze , was a sufficient description of the nucleus. Within, however, the last three years, the whole attitude of physicists to this problem has changed; on one hand, our knowledge of those phenomena which depend on the intimate structure of the nucleus has been greatly increased; on the other hand, wave

mechanics has proved to be eminently suitable for a theoretical attack on this problem, and has already provided a solution of some of the outstanding problems. [中文](#)

Of the many lines of investigation which have been developed, not the least interesting is that of the characteristic electromagnetic radiation that can be emitted by radioactive nuclei. These radiations are termed the γ -rays and are in general of considerably shorter wave-length than the X-rays. They bear the same relation to the structure of the nucleus as do the ordinary optical and X-ray spectra to the structure of the electronic system of the atom, but there is this one point of difference. The optical and X-ray spectra can conveniently be studied for a series of elements because the process of excitation is under control, but it is only in a few isolated cases that it has yet been possible to excite a nucleus by external agencies to emit characteristic radiation. Some of the radioactive bodies, however, emit these radiations spontaneously, since the process of disintegration leaves the newly formed nucleus in an excited state and able to emit its characteristic radiation. The nuclear spectra have therefore only been examined in detail for those radioactive bodies which happen to emit them, and it has been impossible as yet to find any general laws governing the arrangement of these spectra by noting the similarities in the spectra from a succession of different nuclei. [中文](#)

The result of this was that, until a few years ago, while there was a great deal of information about the nuclear spectra of several radioactive bodies, it was still impossible to associate this with any definite feature of the structure. Recently the position has changed greatly, and it now seems possible to view in the nuclear level systems which can be deduced from the γ -ray measurements the characteristic stationary states of α -particles or protons in the nucleus, and to associate such level systems directly with the ground states deducible from other evidence. [中文](#)

Methods of Investigating the γ -rays

A simple method that was of great importance in the early days of radioactivity was to investigate the absorption of the radiation emitted by a particular body by placing a radioactive source at some distance from an electroscope and observing how the ionisation decreased when successive sheets of some material such as aluminium or lead were interposed. It was frequently possible to analyse the resulting absorption curve into a series of simple exponential curves, and thus to obtain a general idea of the different components of the complex radiation. Methods such as this could never yield very precise information, and they have now been superseded by more accurate methods. [中文](#)

The crystal method, in the forms used for X-rays, has been applied with considerable success to γ -rays¹. In one respect the technique is simpler, since in place of the X-ray tube with all the apparatus necessary to run it, it is only necessary to use a fine tube containing the radioactive material, but in other respects the experiments are far more difficult. Owing to the very short wave-length, of the order of 40 X.U. to 4 X.U., the glancing angles are extremely small, and not only is the adjustment of the apparatus considerably more difficult but it is also impossible to measure the wave-length with much accuracy. Further, in comparison with an X-ray tube, the normal amount of radioactive material constitutes an extremely weak source of radiation. As a result it has not yet been possible to push this method when using photographic registration beyond 16 X.U. Recently Steadman² has devised an arrangement, using an electrical counter in place of a photographic plate, which may overcome some of these difficulties. [中文](#)

The method which has given us most of our information is based on the photoelectric effect. The general principle is very simple and is as follows³. A tube containing the radioactive body, the γ -rays of which

are under investigation, is placed inside a small tube of some material of high atomic weight, such as platinum. In their passage through the platinum, the γ -rays eject groups of photoelectrons the energies of which are connected with the frequency of the γ -rays by the Einstein law. Thus the γ -ray of frequency ν will lead to the ejection of a series of groups of electrons of energies $h\nu - K_{Pt}$, $h\nu - L_{Pt}$, etc., according to whether the conversion occurs in the K , L , etc., state of the platinum atoms. This electronic emission can be separated out into a corpuscular spectrum by the usual method of semicircular magnetic focusing. It is usual to register these spectra photographically, and there is not a great deal of difficulty in analysing them and deducing the corresponding γ -rays, since in most cases it is only the electronic group from the K level which is sufficiently intense to give a detectable effect. The general application of the method is greatly limited by the fact that the photographic impression of the groups of electrons always shows as a broad, rather diffuse band. The reason is that, although the photoelectrons are ejected from the platinum atoms with sharply defined energies, only those from the surface of the tube actually emerge with their full velocity. Those from the lower layers are retarded in their passage out, and cause the diffuse character of the band.

[中文](#)

Fortunately, the radioactive atoms themselves provide us with much more favourable opportunities for observing this photoelectric conversion, by what is termed internal conversion. This is by itself an extremely interesting phenomenon, and will be referred to in detail later. For the present purpose it is convenient to describe it as follows. When a radioactive nucleus emits a quantum $h\nu$ of radiation, this does not always escape as such from the atom but may be absorbed by the electronic structure of the atom in its passage out. This internal conversion follows the usual photoelectric laws, and thus a radioactive body which emits γ -rays will also emit a corpuscular spectrum similar in every respect to that coming from the platinum tube already

mentioned, except that the energies are now $h\nu - K_{\text{rad}}$, $h\nu - L_{\text{rad}}$, ... The result is in principle in no way different from the previous case where the γ -rays were converted in the platinum, but the importance of this phenomenon for determining the wave-length of the γ -rays depends on the following facts. If a normal amount of radioactive material is deposited on the surface of a fine wire, the actual number of atoms is so small that the layer is in general less than one atom deep. The electrons liberated by this internal photoelectric effect therefore all escape with their full energy and give extremely sharp lines on a photographic plate, in striking contrast to the broad bands obtained by the normal external photoelectric effect. There is the further advantage that the probability of this internal conversion is so great that measurable lines can be obtained with far shorter exposures than by the other method, and the effects of γ -rays are detectable which are so weak as to be quite unattackable by the other method. [中文](#)

The γ -rays of many radioactive bodies have been analysed by this method, and the main features of the characteristic nuclear spectra are known. The accuracy with which the frequencies can be determined is, however, considerably lower than that realised with X-ray spectra. Even in the case of the bodies radium B and radium C, which have been extensively investigated, the relative frequencies are probably not known to much better than one part in five hundred, and the absolute error may be greater. The chief cause for this lies in the difficulty of obtaining a homogeneous magnetic field over a large area. [中文](#)

Intensities of the γ -rays

An important method⁴ of investigating the intensities has been developed by Skobeltzyn, based on the Compton effect of the γ -rays. A narrow pencil of γ -rays is allowed to pass through an expansion chamber and the recoil electrons liberated by the Compton effect of the γ -rays are observed in the usual manner. In addition, a magnetic

field parallel to the axis of the chamber is applied at the moment of expansion, so that the tracks of the recoil electrons are curved by an amount depending on their velocity. By observing both the curvature and the direction of emission of the recoil electrons, it is possible to associate each electron with a γ -rays of definite frequency. A statistical study is made of the relative number of the recoil electron tracks, and from a knowledge of the general laws of scattering it is possible to deduce the relative intensities of the γ -rays. [中文](#)

Owing to a variety of experimental causes, the resolution of the method is not very high, and the effect of two neighbouring γ -rays cannot always be clearly separated. This disadvantage, however, is far outweighed by the definiteness of the results about the intensity distribution throughout the spectrum, and by the fact that the method detects weak γ -rays equally efficiently as strong γ -rays. The interpretation involves a knowledge of the laws of scattering, but there is both a reasonable theoretical foundation and internal evidence from these experiments which combine to render the uncertainties due to this cause of little importance at present. [中文](#)

The photoelectric method has been applied to determine the intensities of the γ -rays by Ellis and Aston⁵. The corpuscular spectra liberated from the radioactive atoms themselves by the internal conversion are clearly of no use in this connexion, since the relative intensities of the groups depend upon the unknown laws of internal conversion. If, however, the corpuscular spectrum ejected from platinum is observed, we are concerned only with the normal photoelectric effect. Supposing that the X-ray absorption results could be extrapolated to the γ -ray region, it would then be possible to deduce the intensities of the γ -rays from the intensities of the corresponding electronic groups. It is, however, precisely this point which is doubtful, and the accuracy of this method is at present limited by the accuracy of the empirical formula which it was

necessary to assume for the photoelectric method. The method, however, has one extremely important advantage, which is, that if a γ -ray is sufficiently intense to give a measurable corpuscular group, then the intensity of this group can be determined independently of neighbouring weak γ -rays. It will be seen that these two methods are really complementary, one supplying the deficiencies of the other. The γ -rays of radium B and radium C are the only ones that have yet been intensively investigated, but the results seem consistent, and we know not only the general distribution throughout the spectrum but also the individual intensities of all the strong γ -rays. [中文](#)

The results that have just been mentioned referred to the relative intensities of the γ -rays, and in the analogous case of X-rays or optical spectra this would be all that could be stated. However, in the case of the radioactive bodies it is possible to define and to deduce the absolute intensities. This depends upon the fact that the process of excitation is due to the disintegration of the atom. When a nucleus disintegrates, the departure of the disintegration particle, α or β , may leave the nucleus in an excited state, and its subsequent return to its normal state is the cause of the emission of the γ -rays. The γ -rays are, therefore, emitted only after this disintegration, and it is possible to define the absolute intensity of a γ -ray as the average number of quanta emitted per disintegration. It follows that the absolute intensity of any γ -ray cannot be greater than unity. The simplest way of deducing these absolute intensities is to make use of the measurements of the total amount of energy emitted in the form of γ -rays. Knowing both the frequencies and the relative intensities of the γ -rays, it is easy to calculate the average number of quanta of each frequency emitted per disintegration. This further step has already been carried out for the γ -rays of radium B and radium C. [中文](#)

If we now review the information that we possess about the γ -rays of radium B and C and anticipate that which we shall no doubt in time

possess about the rays of other bodies, it will be seen that on the whole it compares very favourably with that available about X-ray spectra. The accuracy of the wave-length determinations is certainly much lower, but we have this important information about the absolute intensities. For example, a prominent γ -ray of radium C has a wave-length of 20.2 X.U., which may be in error by one part in five hundred to even one part in three hundred, but on the other hand, we can say that a quantum of this radiation is emitted by the nucleus on the average twice in every three disintegrations. [中文](#)

Applications to the Structure of the Nucleus

The preceding account will have shown the extent to which the spectroscopy of the γ -rays has advanced. Its application to the problem of nuclear structure is only at the beginning, but it is already possible to indicate the possible lines of advance. [中文](#)

It has been realised for some time that there were many examples of combination differences between the frequencies of the γ -rays from any one body, and that this indicated, what was otherwise probable, that the γ -rays could be associated with a nuclear level system. Little progress, however, was made with this idea for several years, due to the realisation of the difficulty of associating such a level system with any specific part of the nucleus. In the nucleus there are α -particles, protons, and electrons, and in general any of these particles might be the emitters of the γ -rays. This question is still open, but there is now sufficient evidence to make it reasonable to try the hypothesis that the γ -rays are emitted by transitions of α -particles between stationary states in the nucleus. [中文](#)

The theories of Gamow and of Gurney and Condon⁶ have shown that we may regard the process of emissions of an α -particle as due to the gradual leak of the wave function through a potential barrier. An extremely important result of this view is that the energy of the α -

particle outside the atom, which can of course be measured, is the same as the energy of the α -particle in the stationary state in the nucleus which it occupied before the disintegration. For example, the α -particle from radium C is found to be emitted with an energy of 7.68 million volts. We therefore deduce that in the radium C nucleus there is an α -particle level with a positive energy of this amount. Such a level gives a natural basis on which to build the level system deducible from the γ -rays. We imagine that as a result of some internal nuclear arrangement an α -particle is excited to one of certain higher states, and that from these states it arrives at the ground state by emitting γ -rays of frequencies corresponding to the energy differences. It now follows, however, that if an α -particle can leak out through the potential barrier from the ground level, it can do so still more easily from the excited levels. We should therefore expect to find a certain number of high-speed α -particles corresponding to these modes of disintegration. [中文](#)

The existence of such long-range α -particles has of course been known for a long time, and in fact many tentative suggestions have been put forward associating the energy differences of the groups of α -particles with the frequencies of the γ -rays. The present-day point of view, however, goes much further than this, since it predicts definite relations between the intensities of the γ -rays and the number of long-range particles. That such a relation must exist can be easily seen in the following way. Suppose that on the average out of every thousand disintegrations there are n cases where an α -particle is excited to a certain state, the rate of leak through the potential barrier is given to a fair approximation by theory, and the probability of the nuclear transition can at least be estimated. We are therefore able in terms involving only the unknown quantity n to write down the number of long-range α -particles we should expect and the number of quanta of radiation. Both these quantities can also be measured, perhaps not with a very high accuracy, but yet sufficient to see whether there is an

agreement with theory or not. [中文](#)

This is really a stringent test for the theory, because although the theories of the probabilities of nuclear transitions are necessarily tentative, any adjustment which proved necessary for one γ -ray must also apply to all the others. By arguments of this type Fowler⁷ has been led to associate one excited α -particle level of the radium C nucleus with the corresponding nuclear transition formed from the β -ray spectrum. It seems likely that this line of investigation will lead to definite and valuable results. It is of course quite probable that several nuclear transitions will not be able to be associated with long-range α -particles, but it would then be possible to draw the important conclusion that these transitions were due to protons or α -particles of small positive or of negative energy. [中文](#)

Internal Conversion

Reference was made above to internal conversion and it was pointed out that groups of electrons are ejected from the K , L , M states of radioactive atoms with just those energies that they would have if radiation were emitted from the nucleus but was absorbed photoelectrically before it escaped. It has been frequently pointed out that there was no need and, in fact, no justification to assume that in this case the radiation was ever actually emitted at all⁸. All that could be truly inferred from the experimental results was that an excited nucleus could either emit its excess energy as radiation or had some means of transferring this energy to the electronic structure of the atom. [中文](#)

On the old quantum mechanics, it was difficult to imagine any method other than that of radiation transfer, but the wave mechanics suggests that there is a far more intimate connexion between the nuclear particles and the electronic structure. The wave functions of the particles in the nucleus will extend out to a certain extent into the

electronic region of the atom, and conversely the electronic wave functions will exist throughout the nucleus. As a model, we may think that every electron in the atom occasionally passes right through the nucleus, and that a nuclear particle might sometimes for a very short time be found to be actually outside the nucleus. [中文](#)

We have thus no difficulty in seeing, in a general way, how the nuclear energy might be transferred to the electronic system by a direct collision process. Which process, radiation or collision, is predominant can only be settled by experiment, and the answer given by experiment in this case is fortunately unambiguous. The measurements of Ellis and Aston⁵ of the extent of this internal conversion and of the way in which it depends on the frequency of the associated radiation show clearly that the behaviour is incompatible with the radiation hypothesis, and we are thus led to conclude that the collision process is the most important. It will be seen that this process is really a collision of the second kind, between an electron and an excited nucleus. [中文](#)

The peculiar interest of this phenomenon lies in the fact that it represents an easily measurable example of direct interaction between the nucleus and the electronic system. There are several other cases where the interaction between the nucleus and the electronic system must be taken into account, but only in order to give the finer details. The importance of the phenomenon of internal conversion is that the entire phenomenon, even to its first approximation, depends upon interaction, and that no approach can be made to it with a simple point nucleus. [中文](#)

However, quite apart from the intrinsic interest of this interaction, the phenomenon of internal conversion seems likely to provide valuable information about the stationary states in the nucleus. The quantity that can actually be measured, the internal conversion coefficient, is the ratio of the probabilities of occurrence of this collision of the

second kind and of the nuclear radiation transition. The latter is determined mainly by the energy difference of the initial and final states, whilst the absolute energies are involved in the former. In a general way it can be seen that the internal conversion should lead to a classification of the levels responsible for the γ -rays, or, in other words, should enable the γ -rays to be associated with a definite part of the nucleus. 中文

While but little has yet been accomplished along these various lines of investigation of the nuclear levels, it is certainly true that the most difficult step has already been made. The problem can now be clearly envisaged, and definite lines of work proposed which seem likely to lead to results. The way appears open to an experimental investigation of certain radioactive nuclei, and to an interpretation of the experimental results in terms of nuclear phenomena. 中文

(127, 275-278; 1931)

References:

1. Rutherford and Andrade, *Phil. Mag.*, **27**, 854; **28**, 262 (1924). Thibaud, Thèse, Paris (1925). Frilly, Thèse, Paris (1928). Meitner, *Zeit. f. Physik*, **52**, 645 (1928).
2. Steadman, *Phys. Rev.*, **36**, 460 (1930).
3. Ellis, *Proc. Roy. Soc., A*, **101**, 1 (1922). Thibaud, Thèse, Paris (1925).
4. Skobel'tzyn, *Zeit. f. Physik*, **43**, 354 (1927): **58**, 595 (1929).
5. Ellis and Aston, *Proc. Roy. Soc., A*, **129**, 180 (1930).
6. Gamow, *Zeit. f. Physik*, **51**, 204 (1928). Gurney and Condon, *Nature*, **122**, 439 (1928).
7. Fowler, *Proc. Roy. Soc., A*, **129**, 1 (1930).
8. Smekal, *Zeit. f. Physik*, **10**, 275 (1922). *Ann. d. Phys.*, **81**, 399 (1926). Rosseland, *Zeit. f. Physik*, **14**, 173 (1923).

* Substance of two lectures delivered at the Royal Institution on Nov. 4 and 11.

放射性研究的新面貌*

查尔斯·埃利斯

考虑到原子结构在量子理论中的重要地位，物理学家们开始研究原子核的结构。通过观察从放射性原子核发射出的高能电磁辐射—— γ 射线，人们也许可以得到关于原子核内部状态的信息。查尔斯·埃利斯在文中讨论了几种用以研究这种 γ 射线的最有前景的技术。其中最有价值的是测量次级电子能量的技术，在细金属丝表面涂上一层原子那么薄的放射性材料，发生光电效应的原子就会释放出这些次级电子。虽然这种测量 γ 射线能量的方法只能达到1/500的精确度，但埃利斯对用这种方法得到的数据能在不远的未来破解原子核的结构充满信心。 [英文](#)

γ 射线和核结构

直至几年前，物理学的基本问题还是关于原子的结构。通常核是必然要涉及的，但仅涉及其对原子中电子行为的影响。人们发现，在大多数场合净电荷 Ze 足以描述原子核。然而在近三年内，物理学家们对此问题的总体看法已发生了变化，原因如下：一方面，我们对那些依赖于核的本质结构的有关现象的认识已大大增加；另一方面，波动力学已被证明非常适合从理论上攻破这个问题，并且已经为某些重要问题提供了一个解决方式。 [英文](#)

在已经开展的许多研究中，比较令人感兴趣的是对放射性核发射的特征电磁辐射的研究。这些辐射被命名为 γ 射线，它们通常具有比X射线短得多的波长。 γ 射线和核结构的关系就如同普通光及X射线光谱与原子中电子系统结构的关系一样，但是有一点不同：因为激发过程处于控制之下，一系列元素的普通光和X射线光谱很方便进行研究；然而，到目

前为止，仅在个别情况下有可能用外部因素激发一个原子核来发射特征辐射。不过，某些放射体可以自发发射这些辐射，因为衰变过程使新形成的核处于激发态，并能发射其特征辐射。因此，只有那些碰巧发射辐射的放射体的核谱得到了详细的研究，迄今为止尚不太可能通过观察接连的一系列不同原子核核谱的相似性来找出支配这些核谱分布的任何普遍规律。 [英文](#)

直至几年前，尽管有了关于某些放射体核谱的大量信息，但是仍然不可能将其与原子结构的任何确定特性联系在一起。最近，情况发生了很大的变化，现在似乎可以把核中 α 粒子或质子的特征定态看作是由 γ 射线测量推导出的核能级系统中的一部分，并将此能级系统直接与由其他证据推断出的基态相联系。 [英文](#)

研究 γ 射线的方法

在放射性研究早期，一个极为重要的简单方法是研究特殊物体所发射的辐射的吸收，具体做法是将放射源置于与验电器有一定距离的地方，然后观测在接连插入诸如铝或铅这些材料的薄片时，电离如何减小。通常可以将生成的吸收曲线分解成一系列简单的指数曲线，进而大致了解复合辐射中不同组分的情况。利用这类方法不可能得到很精确的信息，因而它们现在已被更精确的方法所代替。 [英文](#)

在X射线研究中所用的晶体方法已经非常成功地应用到了 γ 射线的研究中^[1]。从一方面来看技术上会变得更为简单，因为不再需要X射线管以及运行它所需的所有装置，只需要使用含有放射性材料的细管；但从其他方面来看，实验却要困难得多：由于 γ 射线的波长很短，数量级从40 X.U.到4 X.U.，因此掠射角极小，这不仅使装置的调整更加困难，而且不可能很准确地测量波长。此外，与X射线管比较起来，正常量的放射性材料只是极弱的辐射源。因此，当使用的波长范围超出16 X.U.时，还不能使用这种方法。最近，斯特德曼^[2]已设计了一台装置，用电子计数器来代替照相底片，这也许能克服某些困难。 [英文](#)

基于光电效应的方法已经给我们带来了大部分信息。一般原理非常简单，叙述如下^[3]：将一个装有能放出所要研究的 γ 射线的放射体的

管，放入由某些高原子量材料，例如铂，制成的小管内。在它们通过铂时， γ 射线发射成组的光电子，它们的能量与 γ 射线频率的关系符合爱因斯坦定律。因此，频率为 ν 的 γ 射线将按照转换是否发生在铂原子的 K 、 L 等能量态，发射一系列能量为 $h\nu - K_{Pt}$ 、 $h\nu - L_{Pt}$ 等的光电子群。用一般的半圆磁聚焦方法，可以将这类电子发射分离为微粒谱，通常用照相法记录微粒谱。因为在大多数情况下，只有从 K 能级来的电子群才会有足够的强度产生可检测到的光电效应，所以分析这些谱线以及导出相应的 γ 射线并没有多大的困难。这个方法的普遍推广大大受限于以下事实：电子群的照相印记经常呈现为一个宽而弥散的条带。因为，尽管光电子是以确定的能量从铂原子上发射出来的，但实际上只有管表面的光电子才能全速发射。较底层的电子在发射穿透金属表面的路径上受到阻滞减速，从而引起条带的弥散性。 [英文](#)

所幸的是，放射性原子自身为我们观测这种被称作内转换的光电转换提供了更多有利的机会。这本身就是一个极有趣的现象，后面将详细提及。就目前的目的而言，可方便地将其描述如下：当放射性核发射一个辐射量子 $h\nu$ 时，这个量子并不总会从原子中逃逸，而是可能在逃逸路上被原子的电子结构所吸收。这种内转换遵从通常的光电定律，因此发射 γ 射线的放射体将也会发射微粒谱，各方面都类似于前面提到的来自铂管的微粒谱，只不过现在的能量是 $h\nu - K_{rad}$ 、 $h\nu - L_{rad}$这个结果基本上与以前 γ 射线在铂中转换的情况并无不同，但这类现象对于测定 γ 射线波长的重要性取决于以下事实：将放射性物质的正常量放在细金属丝的表面，那么原子的实际数目会很少，以至于该层通常不到一个原子的深度。因此，这种内部光电效应释放的电子都能以全部能量逃逸，并在照相底片上产生极其清晰的谱线，它与从正常的外部光电效应中得到的宽而弥散的谱线形成鲜明的对比。这种方法还有另一个好处，即这种内转换的概率如此之大，以至于在比其他方法短得多的曝光时间下就可以获得可测量的谱线。在这种情况下 γ 射线的效应是可以检测得到的，而用其他方法很难检测到这种非常微弱的效应。 [英文](#)

人们已用这种方法对许多放射体的 γ 射线作了分析，从而了解了特征核谱的主要特性。然而，用此方法测定 γ 射线频率的准确度比用X射线光谱法测得的要低很多。即使在已经进行过大量研究的镭B和镭C中，也没

有发现相对频率会大大高于 $1/500$ ，绝对误差可能更大。其主要原因是，在一个较大的范围内，要获得均匀磁场是有困难的。 [英文](#)

γ 射线的强度

斯科别利兹根据 γ 射线的康普顿效应已建立了一种研究 γ 射线强度的重要方法^[4]。让一束 γ 射线的窄光锥通过膨胀室，并以常规方式观测由 γ 射线的康普顿效应释放的反冲电子。此外，在膨胀瞬间，施加一个方向平行于膨胀室轴线的磁场，于是反冲电子轨迹的弯曲度取决于其速度。通过观测反冲电子发射轨迹的曲率和方向，可以将每个电子与确定频率的 γ 射线联系起来。通过对反冲电子轨迹的相对数进行统计研究，并根据散射的基本定律，可以推导出 γ 射线的相对强度。 [英文](#)

由于各种实验原因，这种方法的分辨率不是很高，并且也不是总能将两个相邻 γ 射线的效应清楚地分开。然而，以下两个优点的价值在很大程度上掩盖了这个缺点：其一是能得到整个谱线结果中 γ 射线强度的确定分布，其二是这种方法检测弱 γ 射线与检测强 γ 射线一样有效。数据的解释需要用到散射定律的知识，但是有合理的理论基础和来自这些实验本身的证据，这两者的结合使得目前散射知识带来的不确定性变得无关紧要了。 [英文](#)

埃利斯和阿斯顿^[5]已将光电方法应用于测定 γ 射线的强度。放射性原子本身通过内转换释放的微粒谱显然不能用于与此相关联的问题，因为成组光电子的相对强度与尚不为人所知的内转换定律有关。然而，如果观测从铂中发射的微粒谱，我们可以只关心正常的光电效应。假定X射线的吸收结果可以外推到 γ 射线区，那么从相应的电子群强度推导 γ 射线的强度就将成为可能。然而，不可靠的恰恰是这一点，目前这种方法的准确度受限在于光电方法中必须假设的经验公式的准确度。然而，这种方法具有一个极其重要的优点，即如果 γ 射线的强度强到足以获得可测的微粒电子群，那么这组电子强度的测定可与邻近的弱 γ 射线无关。由此可见，这两种方法实际上是互补的，一种方法弥补了另一种方法的缺陷。虽然镭B和镭C的 γ 射线是迄今为止唯一得到深入研究的 γ 射线，但结果似乎是一致的，我们不仅知道了 γ 射线整个光谱的大致分布，而且知道了所有强 γ 射线各自的强度。 [英文](#)

上面所提到的结果指的是 γ 射线的相对强度。如果是在与X射线或光学光谱类似的情况下，相对强度将是所能说明的全部情况。不过，在放射体的情况下，要确定和推导出绝对强度是可能的。这是因为激发过程是由于原子的衰变造成的。当原子核衰变时，会释放出衰变粒子（ α 粒子或者 β 粒子），从而有可能使核处于激发态，随后它又回到正常态，并发射 γ 射线。因此， γ 射线仅在这类衰变之后发射，可以将 γ 射线的绝对强度定义为每次衰变发射的平均量子数。由此可以断定，任何 γ 射线的绝对强度都不能大于1个单位。导出这些绝对强度的最简单的方法是利用对以 γ 射线形式发射的总能量的测量结果。知道了 γ 射线的频率和相对强度，就很容易计算出每次衰变时发射的对应于每个频率的平均量子数。人们已经对镭B和镭C的 γ 射线应用了这种深层次的研究方法。

英文

如果现在回顾一下我们所拥有的关于镭B和镭C的 γ 射线的信息，并预期我们无疑将及时获得其他放射体 γ 射线的信息，就会发现，与从X射线光谱得到的可用信息相比， γ 射线的信息在总体上是非常令人满意的。测定波长的准确度确实会降低很多，但我们有了绝对强度的重要信息。例如，镭C的一种主要 γ 射线的波长为20.2 X.U.，其误差可能为1/500，甚至可以达到1/300，但另一方面，我们也可以说，原子核在每三次衰变中平均辐射两次这样的量子。

英文

在核结构研究中的应用

前面的叙述显示出 γ 射线光谱学已经发展到了怎样的程度。虽然将其应用于解决核结构问题仅仅是刚刚起步，但我们已经可以看到可能的发展方向。

英文

之前人们就已经认识到，有许多例子显示来自任何一个放射体的 γ 射线在频率上存在多组差异，这表明 γ 射线可能与核能级系统相关，尽管别的解释也有可能。然而，多年以来，由于很难将这样一个核能级系统与核的任何特定部分联系起来，因而人们在这一构想上没有取得什么进展。在核中，存在 α 粒子、质子和电子，一般来说这些粒子中的任何一个都有可能发射 γ 射线，这个问题仍然是一个尚未解决的问题。但是，现在有足够的证据说明这样去假设是合理的，即认为 γ 射线是因核内 α 粒

子在定态之间的跃迁而发射的。

[英文](#)

伽莫夫以及格尼和康登的理论^[6]指出，我们可以认为 α 粒子的发射过程是由于波函数通过势垒的逐渐泄漏。由这个观点可以得到一个极为重要的结果，即原子外面 α 粒子的能量（当然可以测量）与核衰变前在核中处于定态的 α 粒子的能量相等。例如，我们发现镭C发射的 α 粒子能量是7.68百万电子伏特。于是可以推出，在镭C的核内，存在一个具有7.68百万电子伏特正能量的 α 粒子能级。这一能级给出了建立根据 γ 射线推导的能级系统的自然基础。我们可以设想，某些内核排列激发 α 粒子，使其到达某一个更高的激发态，然后通过发射频率相当于能量差的 γ 射线又从激发态回到基态。然而，如果一个 α 粒子在从基态能级穿过势垒时会泄漏，那么它就更容易从激发态能级泄漏。因此我可以预期将发现有一定数量的高速 α 粒子与这些衰变模式相对应。

[英文](#)

诚然，很久以前我们就知道这类长程 α 粒子是存在的，事实上我们已提出过很多将 α 粒子群的能量差与 γ 射线的频率联系起来的初步建议。然而，目前的观点比这已更进了一步，因为它预测了 γ 射线强度与长程 α 粒子数量之间的确定关系。通过以下方式很容易看出这种确定关系是必然存在的：假定平均每千次衰变有 n 个 α 粒子被激发到某个激发态上，根据理论可以非常好地近似得到穿出势垒的泄漏率，因而至少可以估计出核跃迁的概率。因此我们能够用只包含未知数 n 的项写出我们所预期的长程 α 粒子的数量及 γ 辐射的量子数。这两个量都可以通过测量得到，也许准确度不是很高，但已足以了解它与理论是否一致。

[英文](#)

这实际上是对理论的严格检验，因为虽然核跃迁概率理论目前还不够完备，但是，被一种 γ 射线证明是必要的调整也应适用于所有其他的 γ 射线。这种观点引导福勒^[7]将镭C核 α 粒子的一个激发态能级与 β 射线谱形成的相应核跃迁联系起来。看起来这类研究路线有可能会确定和有价值的结果。当然完全有可能，一些核跃迁与长程 α 粒子不相联系，但由此可能得出如下重要结论：这些核跃迁是由具有微正能量或负能量的质子或 α 粒子产生的。

[英文](#)

内转换

上面已经提到了内转换，并已指出从放射性原子的 K 、 L 、 M 态发射出来的电子群所具有的能量刚好等于如果这些从核中发出的辐射量子在逃逸前被光电吸收的能量。已屡次指出，假定在内转换情况下 γ 光子会完全发射出来是没有必要的，也是不正确的^[8]。根据实验结果能够真正推出来的是，一个激发核或者会以辐射形式发射其过剩的能量，或者会以一些方式将这类能量传递给原子的电子结构。 [英文](#)

按照旧的量子论，很难想象除了辐射转换之外还有其它方法，但波动力学提出，在核粒子与电子结构之间存在着更为密切的联系。核内粒子的波函数将在一定程度上延伸到原子的电子区域，反过来，电子的波函数也将存在于整个核内。作为模型，我们可以认为，原子中的每一个电子都偶尔会穿过核，核粒子实际上有时也可能在核外出现很短的时间。 [英文](#)

因此我们不难看出，在一般情况下，核能量可通过直接碰撞过程转移到电子系统。辐射还是碰撞，这两种过程哪一个更占优势只能通过实验来确定。幸运的是，在这种情况下由实验给出的回答是明确的。埃利斯和阿斯顿^[5]对内转换的程度以及它对相关辐射频率的依赖方式进行了测量，结果明确显示出与辐射假说的不相容。因此，我们得出的结论是碰撞过程才是最重要的。我们将会看到这个过程实际上是电子与激发核的第二类碰撞。 [英文](#)

这种现象之所以具有特殊意义是因为它代表了核与电子系统之间发生直接相互作用的一个易于测量的例子。还有其他几种情况必须考虑核与电子系统之间的相互作用，但只是为了给出更精细的细节。内转换现象的重要性是整个现象（即使在一级近似下）依赖于核与电子的相互作用，哪种方法都不可能仅仅把原子核看成点粒子。 [英文](#)

然而，除了对这类相互作用本身的意义之外，内转换现象似乎还能提供关于核内定态的重要信息。实际上能被测量的量是内转换系数，它是第二类碰撞与核辐射跃迁出现概率的比值。后者主要由初态和终态的能量差决定，而前者涉及绝对能量。就通常意义而论，内转换将导致引起 γ 射线发射的能级分类，换言之，它可将 γ 射线与核的某个确定部分联系起来。 [英文](#)

尽管人们以各种方式对核能级的研究尚未取得明显的进展，不过，可以肯定的是我们已迈出了最困难的一步。现在可以清晰地设想问题，并且可以提出有可能得到结果的明确工作路线。这种方式为用实验研究某些放射性核以及根据核现象解释实验结果提供了可能。 [英文](#)

（沈乃澂 翻译；尚仁成 审稿）

* 本文中的内容来自作者11月4日和11日发表于英国皇家研究院的两个报告。

The End of the World: from the Standpoint of Mathematical Physics*

A. S. Eddington

This supplement contains a somewhat light-hearted address on “the end of the world” that Arthur Eddington delivered at the Mathematical Association. One must first ask “which end?”, he says. Space itself may have no end: current cosmology suggested a universe shaped like the surface of a sphere, finite but without edges. As for time, the second law of thermodynamics suggests that the entire universe will eventually reach a state of thermodynamic equilibrium marked by complete disorganisation. However, if time is infinite then every conceivable fluctuation in the universe’s particles will happen, temporarily disturbing this equilibrium. Eddington ends by predicting how the world will really end: as a ball of radiation growing ever larger, roughly doubling its size every 1,500 million years. [中文](#)

THE world—or space-time—is a four-dimensional continuum, and consequently offers a choice of a great many directions in which we might start off to look for an end; and it is by no means easy to describe “from the standpoint of mathematical physics” the direction in which I intend to go. I have therefore to examine at some length the preliminary question, Which end? [中文](#)

Spherical Space

We no longer look for an end to the world in its space dimensions. We have reason to believe that so far as its space dimensions are concerned the world is of spherical type. If we proceed in any direction in space we do not come to an end of space, nor do we continue on to infinity; but, after travelling a certain distance (not inconceivably great), we find ourselves back at our starting-point, having “gone round the world”. A continuum with this property is said to be finite but unbounded. The surface of a sphere is an example of a finite but unbounded two-dimensional continuum; our actual three-dimensional space is believed to have the same kind of connectivity, but naturally the extra dimension makes it more difficult to picture. If we attempt to picture spherical space, we have to keep in mind that it is the *surface* of the sphere that is the analogue of our three-dimensional space; the inside and the outside of the sphere are fictitious elements in the picture which have no analogue in the actual world. [中文](#)

We have recently learnt, mainly through the work of Prof. Lemaître, that this spherical space is expanding rather rapidly. In fact, if we wish to travel round the world and get back to our starting-point, we shall have to move faster than light; because, whilst we are loitering on the way, the track ahead of us is lengthening. It is like trying to run a race in which the finishing-tape is moving ahead faster than the runners. We can picture the stars and galaxies as embedded in the surface of a rubber balloon which is being steadily inflated; so that, apart from their individual motions and the effects of their ordinary gravitational attraction on one another, celestial objects are becoming farther and farther apart simply by the inflation. It is probable that the spiral nebulae are so distant that they are very little affected by mutual gravitation and exhibit the inflation effect in its pure form. It has been known for some years that they are scattering apart rather

rapidly, and we accept their measured rate of recession as a determination of the rate of expansion of the world. 中文

From the astronomical data it appears that the original radius of space was 1,200 million light years. Remembering that distances of celestial objects up to several million light years have actually been measured, that does not seem overwhelmingly great. At that radius the mutual attraction of the matter in the world was just sufficient to hold it together and check the tendency to expand. But this equilibrium was unstable. An expansion began, slow at first; but the more widely the matter was scattered the less able was the mutual gravitation to check the expansion. We do not know the radius of space today, but I should estimate that it is not less than ten times the original radius. 中文

At present our numerical results depend on astronomical observations of the speed of scattering apart of the spiral nebulae. But I believe that theory is well on the way to obtaining the same results independently of astronomical observation. Out of the recession of the spiral nebulae we can determine not only the original radius of the universe but also the total mass of the universe, and hence the total number of protons in the world. I find this number to be either 7×10^{78} or 14×10^{78} .† I believe that this number is very closely connected with the ratio of the electrostatic and the gravitational units of force, and, apart from a numerical coefficient, is equal to the square of the ratio. If F is the ratio of the electrical attraction between a proton and electron to their gravitational attraction, we find $F^2 = 5.3 \times 10^{78}$. There are theoretical reasons for believing that the total number of particles in the world is αF^2 , where α is a simple geometrical factor (perhaps involving π). It ought to be possible before long to find a theoretical value of α , and so make a complete connexion between the observed rate of expansion of the universe and the ratio of electrical and gravitational forces. 中文

I must not dally over space any longer but must turn to time. The world is closed in its space dimensions but is open in both directions in its time dimension. Proceeding from “here” in any direction in space we ultimately come back to “here”; but proceeding from “now” towards the future or the past we shall never come across “now” again. There is no bending round of time to bring us back to the moment we started from. In mathematics this difference is provided for by the symbol $\sqrt{-1}$, just as the same symbol crops up in distinguishing a closed ellipse and an open hyperbola. 中文

If, then, we are looking for an end of the world—or, instead of an end, an indefinite continuation for ever and ever—we must start off in one of the two time directions. How shall we decide which of these two directions to take? It is an important question. Imagine yourself in some unfamiliar part of space-time so as not to be biased by conventional landmarks or traditional standards of reference. There ought to be a signpost with one arm marked “To the future” and the other arm marked “To the past”. My first business is to find this signpost, for if I make a mistake and go the wrong way I shall lead you to what is no doubt an “end of the world”, but it will be that end which is more usually described as the *beginning*. 中文

In ordinary life the signpost is provided by consciousness. Or perhaps it would be truer to say that consciousness does not bother about signposts; but wherever it finds itself it goes off on urgent business in a particular direction, and the physicist meekly accepts its lead and labels the course it takes “To the future”. It is an important question whether consciousness in selecting its direction is guided by anything in the physical world. If it is guided, we ought to be able to find directly what it is in the physical world which makes it a one-way street for conscious beings. The view is sometimes held that the “going on of time” does not exist in the physical world at all and is a purely subjective impression. According to that view, the difference between

past and future in the material universe has no more significance than the difference between right and left. The fact that experience presents space-time as a cinematograph film which is always unrolled in a particular direction is not a property or peculiarity of the film (that is, the physical world) but of the way it is inserted into the cinematograph (that is, consciousness). In fact, the one-way traffic in time arises from the way our material bodies are geared on to our consciousness:

“Nature has made our gears in such a way
That we can never get into reverse”. 中文

If this view is right, “the going on of time” should be dropped out of our picture of the physical universe. Just as we have dropped the old geocentric outlook and other idiosyncrasies of our circumstances as observers, so we must drop the dynamic presentation of events which is no part of the universe itself but is introduced in our peculiar mode of apprehending it. In particular, we must be careful not to treat a past-to-future presentation of events as truer or more significant than a future-to-past presentation. We must, of course, drop the theory of evolution, or at least set alongside it a theory of anti-evolution as equally significant. 中文

If anyone holds this view, I have no argument to bring against him. I can only say to him, “You are a teacher whose duty it is to inculcate in youthful minds a true and balanced outlook. But you teach (or without protest allow your colleagues to teach) the utterly one-sided doctrine of evolution. You teach it not as a colourless schedule of facts but as though there were something significant, perhaps even morally inspiring, in the progress from formless chaos to perfected adaptation. This is dishonest; you should also treat it from the equally significant point of view of anti-evolution and discourse on the progress from future to past. Show how from the diverse forms of life existing today Nature anti-evolved forms which were more and more unfitted to

survive, until she reached the sublime crudity of the palaeozoic forms. Show how from the solar system Nature anti-evolved a chaotic nebula. Show how, in the course of progress from future to past, Nature took a universe which, with all its faults, is not such a bad effort of architecture and—in short, made a hash of it.” [中文](#)

Entropy and Disorganisation

Leaving aside the guidance of consciousness, we have found it possible to discover a kind of signpost for time in the physical world. The signpost is of rather a curious character, and I would scarcely venture to say that the discovery of the signpost amounts to the same thing as the discovery of an objective “going on of time” in the universe. But at any rate it serves to discriminate past and future, whereas there is no corresponding objective distinction of left and right. The distinction is provided by a certain measurable quantity called entropy. Take an isolated system and measure its entropy S at two instants t_1 and t_2 . We want to know whether t_1 is earlier or later than t_2 without employing the intuition of consciousness, which is too disreputable a witness to trust in mathematical physics. The rule is that the instant which corresponds to the greater entropy is the later. In mathematical form

$$dS/dt \text{ is always positive.}$$

This is the famous second law of thermodynamics. [中文](#)

Entropy is a very peculiar conception, quite unlike the conceptions ordinarily employed in the classical scheme of physics. We may most conveniently describe it as the measure of disorganisation of a system. Accordingly, our signpost for time resolves itself into the law that disorganisation increases from past to future. It is one of the most curious features of the development of physics that the entropy outlook grew up quietly alongside the ordinary analytical outlook for a great many years. Until recently it always “played second fiddle”; it

was convenient for getting practical results, but it did not pretend to convey the most penetrating insight. But now it is making a bid for supremacy, and I think there is little doubt that it will ultimately drive out its rival. [中文](#)

There are some important points to emphasise. First, there is no other independent signpost for time; so that if we discredit or “explain away” this property of entropy, the distinction of past and future in the physical world will disappear altogether. Secondly, the test works consistently; isolated systems in different parts of the universe agree in giving the same direction of time. Thirdly, in applying the test we must make certain that our system is strictly isolated. Evolution teaches us that more and more highly organised systems develop as time goes on; but this does not contradict the conclusion that on the whole there is a loss of organisation. It is partly a question of definition of organisation; from the evolutionary point of view it is quality rather than quantity of organisation that is noticed. But, in any case, the high organisation of these systems is obtained by draining organisation from other systems with which they come in contact. A human being as he grows from past to future becomes more and more highly organised—at least, he fondly imagines so. But if we make an isolated system of him, that is to say, if we cut off his supply of food and drink and air, he speedily attains a state which everyone would recognise as “a state of disorganisation”. [中文](#)

It is possible for the disorganisation of a system to become complete. The state then reached is called thermodynamic equilibrium. The entropy can increase no further, and, since the second law of thermodynamics forbids a decrease, it remains constant. Our signpost for time disappears; and so far as that system is concerned, time ceases to go on. That does not mean that time ceases to exist; it exists and extends just as space exists and extends, but there is no longer any one-way property. It is like a one-way street on which there is never

any traffic. [中文](#)

Let us return to our signpost. Ahead there is ever-increasing disorganisation. Although the sum total of organisation is diminishing, certain parts of the universe are exhibiting a more and more highly specialised organisation; that is the phenomenon of evolution. But ultimately this must be swallowed up in the advancing tide of chance and chaos, and the whole universe will reach a state of complete disorganisation—a uniform featureless mass in thermodynamic equilibrium. This is the end of the world. Time will *extend* on and on, presumably to infinity. But there will be no definable sense in which it can be said to *go on*. Consciousness will obviously have disappeared from the physical world before thermodynamical equilibrium is reached, and dS/dt having vanished, there will remain nothing to point out a direction in time. [中文](#)

The Beginning of Time

It is more interesting to look in the opposite direction—towards the past. Following time backwards, we find more and more organisation in the world. If we are not stopped earlier, we must come to a time when the matter and energy of the world had the maximum possible organisation. To go back further is impossible. We have come to an abrupt end of space-time—only we generally call it the “beginning”.

[中文](#)

I have no “philosophical axe to grind” in this discussion. Philosophically, the notion of a beginning of the present order of Nature is repugnant to me. I am simply stating the dilemma to which our present fundamental conception of physical law leads us. I see no way round it; but whether future developments of science will find an escape I cannot predict. The dilemma is this:—Surveying our surroundings, we find them to be far from a “fortuitous concourse of atoms”. The picture of the world, as drawn in existing physical

theories, shows arrangement of the individual elements for which the odds are multillions to 1 against an origin by chance. Some people would like to call this non-random feature of the world purpose or design; but I will call it non-committally anti-chance. We are unwilling to admit in physics that anti-chance plays any part in the reactions between the systems of billions of atoms and quanta that we study; and indeed all our experimental evidence goes to show that these are governed by the laws of chance. Accordingly, we sweep anti-chance out of the laws of physics—out of the differential equations. Naturally, therefore, it reappears in the boundary conditions, for it must be got into the scheme somewhere. By sweeping it far enough away from the sphere of our current physical problems, we fancy we have got rid of it. It is only when some of us are so misguided as to try to get back billions of years into the past that we find the sweepings all piled up like a high wall and forming a boundary—a beginning of time—which we cannot climb over. [中文](#)

A way out of the dilemma has been proposed which seems to have found favour with a number of scientific workers. I oppose it because I think it is untenable, not because of any desire to retain the present dilemma. I should like to find a genuine loophole. But that does not alter my conviction that the loophole that is at present being advocated is a blind alley. I must first deal with a minor criticism.

[中文](#)

I have sometimes been taken to task for not sufficiently emphasising in my discussion of these problems that the results about entropy are a matter of probability, not of certainty. I said above that if we observe a system at two instants, the instant corresponding to the greater entropy will be the later. Strictly speaking, I ought to have said that for a smallish system the chances are, say, 10^{20} to 1, that it is the later. Some critics seem to have been shocked at my lax morality in making such a statement, when I was well aware of the 1 in 10^{20}

chance of its being wrong. Let me make a confession. I have in the past twenty-five years written a good many papers and books, broadcasting a large number of statements about the physical world. I fear that for not many of these statements is the risk of error so small as 1 in 10^{20} . Except in the domain of pure mathematics, the trustworthiness of my conclusions is usually to be rated at nearer 10 to 1 than 10^{20} to 1; even that may be unduly boastful. I do not think it would be for the benefit of the world that no statement should be allowed to be made if there were a 1 in 10^{20} chance of its being untrue; conversation would languish somewhat. The only persons entitled to open their mouths would presumably be the pure mathematicians. 中文

Fluctuations

The loophole to which I referred depends on the occurrence of chance fluctuations. If we have a number of particles moving about at random, they will in the course of time go through every possible configuration, so that even the most orderly, the most non-chance configuration, will occur by chance if only we wait long enough. When the world has reached complete disorganisation (thermodynamic equilibrium) there is still infinite time ahead of it, and its elements will thus have opportunity to take up every possible configuration again and again. If we wait long enough, a number of atoms will, just by chance, arrange themselves in systems as they are at present arranged in this room; and, just by chance, the same sound-waves will come from one of these systems of atoms as are at present emerging from my lips; they will strike the ears of other systems of atoms, arranged just by chance to resemble you, and in the same stages of attention or somnolence. This mock Mathematical Association meeting must be repeated many times over—an infinite number of times, in fact—before t reaches $+\infty$. Do not ask me whether I expect you to believe that this will really happen.‡ 中文

“Logic is logic. That’s all I say.”

中文

So, after the world has reached thermodynamical equilibrium the entropy remains steady at its maximum value, except that “once in a blue moon” the absurdly small chance comes off and the entropy drops appreciably below its maximum value. When this fluctuation has died out, there will again be a very long wait for another coincidence giving another fluctuation. It will take multillions of years, but we have all infinity of time before us. There is no limit to the amount of the fluctuation, and if we wait long enough we shall come across a big fluctuation which will take the world as far from thermodynamical equilibrium as it is at the present moment. If we wait for an enormously longer time, during which this huge fluctuation is repeated untold numbers of times, there will occur a still larger fluctuation which will take the world as far from thermodynamical equilibrium as it was one second ago. 中文

The suggestion is that we are now on the downward slope of one of these fluctuations. It has quite a pleasant subtlety. Is it chance that we happen to be running down the slope and not toiling up the slope? Not at all. So far as the physical universe is concerned, we have *defined* the direction of time as the direction from greater to less organisation, so that, on whichever side of the mountain we stand, our signpost will point downhill. In fact, on this theory, the going on of time is not a property of time in general, but is a property of the slope of the fluctuation on which we are standing. Again, although the theory postulates a universe involving an extremely improbable coincidence, it provides an infinite time during which the most improbable coincidence might occur. Nevertheless, I feel sure that the argument is fallacious. 中文

If we put a kettle of water on the fire there is a chance that the water will freeze. If mankind goes on putting kettles on the fire until $t = \infty$, the chance will one day come off and the individual concerned will be

somewhat surprised to find a lump of ice in his kettle. But it will not happen to *me*. Even if tomorrow the phenomenon occurs before my eyes, I shall not explain it this way. I would much sooner believe in interference by a demon than in a coincidence of that kind coming off; and in doing so I shall be acting as a rational scientist. The reason why I do not at present believe that devils interfere with my cooking arrangements and other business, is because I have become convinced by experience that Nature obeys certain uniformities which we call laws. I am convinced because these laws have been tested over and over again. But it is possible that every single observation from the beginning of science which has been used as a test, has just happened to fit in with the law by a chance coincidence. It would be an improbable coincidence, but I think not quite so improbable as the coincidence involved in my kettle of water freezing. So if the event happens and I can think of no other explanation, I shall have to choose between two highly improbable coincidences: (a) that there are no laws of Nature and that the apparent uniformities so far observed are merely coincidences; (b) that the event is entirely in accordance with the accepted laws of Nature, but that an improbable coincidence has happened. I choose the former because mathematical calculation indicates that it is the less improbable. I reckon a sufficiently improbable coincidence as something much more disastrous than a violation of the laws of Nature; because my whole reason for accepting the laws of Nature rests on the assumption that improbable coincidences do not happen—at least, that they do not happen in my experience. § 中文

Similarly, if logic predicts that a mock meeting of the Mathematical Association will occur just by a fortuitous arrangement of atoms before $t = \infty$, I reply that I cannot possibly accept that as being the explanation of a meeting of the Mathematical Association in $t = 1931$. We must be a little careful over this, because there is a trap for the unwary. The year 1931 is not an absolutely random date between $t =$

$-\infty$ and $t = +\infty$. We must not argue that because for only $1/x$ th of time between $t = -\infty$ and $t = \infty$ a fluctuation as great as the present one is in operation, therefore the chances are x to 1 against such a fluctuation occurring in the year 1931. For the purposes of the present discussion, the important characteristic of the year 1931 is that it belongs to a period during which there exist in the universe beings capable of speculating about the universe and its fluctuations. Now I think it is clear that such creatures could not exist in a universe in thermodynamical equilibrium. A considerable degree of deviation is required to permit of living beings. Therefore it is perfectly fair for supporters of this suggestion to wipe out of account all those multillions of years during which the fluctuations are less than the minimum required to permit of the development and existence of mathematical physicists. That greatly diminishes x , but the odds are still overpowering. The *crude* assertion would be that (unless we admit something which is not chance in the architecture of the universe) it is practically certain that at any assigned date the universe will be almost in the state of maximum disorganisation. The *amended* assertion is that (unless we admit something which is not chance in the architecture of the universe) it is practically certain that a universe containing mathematical physicists will at any assigned date be in the state of maximum disorganisation which is not inconsistent with the existence of such creatures. I think it is quite clear that neither the original nor the amended version applies. We are thus driven to admit anti-chance; and apparently the best thing we can do with it is to sweep it up into a heap at the beginning of time, as I have already described. 中文

The connexion between our entropy signpost and that dynamic quality of time which we describe as “going on” or “becoming” leads to very difficult questions which I cannot discuss here. The puzzle is that the signpost seems so utterly different from the thing of which it is supposed to be the sign. The one thing on which I have to insist is

that, apart from consciousness, the increase of entropy is the only trace that we can find of a one-way direction of time. I was once asked a ribald question: How does an electron (which has not the resource of consciousness) remember which way time is going? Why should it not inadvertently turn round and, so to speak, face time the other way? Does it have to calculate which way entropy is increasing in order to keep itself straight? I am inclined to think that an electron does do something of that sort. For an electric charge to face the opposite way in time is the same thing as to change the sign of the charge. So if an electron mistook the way time was going it would turn into a positive charge. Now, it has been one of the troubles of Dr. P. A. M. Dirac that in the mathematical calculations based on his wave equation the electrons do sometimes forget themselves in this way. As he puts it, there is a finite chance of the charge changing sign after an encounter. You must understand that they only do this in the mathematical problems, not in real life. It seems to me there is good reason for this. A mathematical problem deals with, say, four electric charges at the most; that is about as many as a calculator would care to take on. Accordingly, the unfortunate electron in the problem has to make out the direction of past to future by watching the organisation of three other charges. Naturally, it is deceived sometimes by chance coincidences which may easily happen when there are only three particles concerned; and so it has a good chance of facing the wrong way and becoming a positive charge. But in any real experiment we work with apparatus containing billions of particles—ample to give the electron its bearings with certainty. Dirac's theory predicts things which never happen, simply because it is applied to problems which never occur in Nature. When it is applied to four particles alone in the universe, the analysis very properly brings out the fact that in such a system there could be no steady one-way direction of time, and vagaries would occur which are guarded against in our actual universe consisting of about 10^{79} particles.

Heisenberg's Principle

A discussion of the properties of time would be incomplete without a reference to the principle of indeterminacy, which was formulated by Heisenberg in 1927 and has been generally accepted. It had already been realised that theoretical physics was drifting away from a deterministic basis; Heisenberg's principle delivered the knock-out blow, for it actually postulated a certain measure of indeterminacy or unpredictability of the future as a fundamental law of the universe. This change of view seems to make the progress of time a much more genuine thing than it used to be in classical physics. Each passing moment brings into the world something new—something which is not merely a mathematical extrapolation of what was already there.

中文

The deterministic view which held sway for at least two centuries was that if we had complete data as to the state of the whole universe during, say, the first minute of the year 1600, it would be merely a mathematical exercise to deduce everything that has happened or will happen at any date in the future or past. The future would be determined by the present as the solution of a differential equation is determined by the boundary conditions. To understand the new view, it is necessary to realise that there is a risk of begging the question when we use the phrase “complete data”. All our knowledge of the physical world is inferential. I have no direct acquaintance with my pen as an object in the physical world; I infer its existence and properties from the light waves which fall on my eyes, the pressure waves which travel up my muscles, and so on. 中文

Precisely the same scheme of inference leads us to infer the existence of things in the past. Just as I infer a physical object, namely, my pen, as the cause of certain visual sensations now, so I may infer an infection some days ago as the cause of an attack of measles. If we follow out this principle completely we shall infer causes in the year

1600 for all the events which we know to have happened in 1930. At first sight it would seem that these inferred causes have just as much status in the physical world as my fountain pen, which is likewise an inferred cause. So the determinist thinks he has me in a cleft stick. If the scientific worker poking about in the universe in 1600 comes across these causes, then he has all the data for making a correct prediction for 1930; if he does not, then he clearly has not complete knowledge of the universe in 1600, for these causes have as much right to the status of physical entities as any of our other inferences.

中文

I need scarcely stop to show how this begs the question by arbitrarily prescribing what we should deem to be complete knowledge of the universe in 1600, irrespective of whether there is any conceivable way in which this knowledge could be obtained at the time. What Heisenberg discovered was that (at least in a wide range of phenomena embracing the whole of atomic physics and electron theory) there is a provision of Nature that just half of the data demanded by our determinist friend might with sufficient diligence be collected by the investigators in 1600, and that complete knowledge of this half would automatically exclude all knowledge of the other half. It is an odd arrangement, because you can take your choice which half you will find out; you can know either half but not both halves. Or you can make a compromise and know both halves imperfectly, that is, with some margin of uncertainty. But the rule is definite. The data are linked in pairs and the more accurately you measure one member of the pair the less accurately you can measure the other member.

中文

Both halves are necessary for a complete prediction of the future, although, of course, by judiciously choosing the type of event we predict we can often make safe prophecies. For example, the principle of indeterminacy will obviously not interfere with my prediction that

during the coming year zero will turn up approximately $\frac{1}{37}$ of the total number of times the roulette ball is spun at Monte Carlo. All our successful predictions in physics and astronomy are on examination found to depend on this device of eliminating the inherent uncertainty of the future by averaging. 中文

As an illustration, let us consider the simplest type of prediction. Suppose we have a particle, say an electron, moving undisturbed with uniform velocity. If we know its position now and its velocity, it is a simple matter to predict its position at some particular future instant. Heisenberg's principle asserts that the position and velocity are paired data; that is to say, although there is no limit to the accuracy with which we might get to know the position and no limit to the accuracy with which we might get to know the velocity, we cannot get to know both. So our attempt at an accurate prediction of the future position of the particle is frustrated. We can, if we like, observe the position now and the position at the future instant with the utmost accuracy (since these are not paired data) and then calculate what has been the velocity in the meantime. Suppose that we use this velocity together with the original position to compute the second position. Our result will be quite correct, and we shall be true prophets—after the event.

中文

This principle is so fully incorporated into modern physics that in wave mechanics the electron is actually pictured in a way which exhibits this “interference” of position and velocity. To attribute to it exact position and velocity simultaneously would be inconsistent with the picture. Thus, according to our present outlook, the absence of one half of the data of prediction is not to be counted as ignorance; the data are lacking because they do not come into the world until it is too late to make the prediction. They come into existence when the event is accomplished. 中文

I suppose that to justify my title I ought to conclude with a prophecy

as to what the end of the world will be like. I confess I am not very keen on the task. I half thought of taking refuge in the excuse that, having just explained that the future is unpredictable, I ought not to be expected to predict it. But I am afraid that someone would point out that the excuse is a thin one, because all that is required is a computation of averages and that type of prediction is not forbidden by the principle of indeterminacy. It used to be thought that in the end all the matter of the universe would collect into one rather dense ball at uniform temperature; but the doctrine of spherical space, and more especially the recent results as to the expansion of the universe, have changed that. There are one or two unsettled points which prevent a definite conclusion, so I will content myself with stating one of several possibilities. It is widely thought that matter slowly changes into radiation. If so, it would seem that the universe will ultimately become a ball of radiation growing ever larger, the radiation becoming thinner and passing into longer and longer wavelengths. About every 1,500 million years it will double its radius, and its size will go on expanding in this way in geometrical progression for ever.

中文

(127, 447-453; 1931)

* Presidential address to the Mathematical Association, delivered on Jan. 5.

† This ambiguity is inseparable from the operation of counting the number of particles in finite but unbounded space. It is impossible to tell whether the protons have been counted once or twice over.

‡ I am hopeful that the doctrine of the “expanding universe” will intervene to prevent its happening.

§ No doubt “extremely improbable” coincidences occur to all of us, but the improbability is of an utterly different order of magnitude from that concerned in the present discussion.

以数学物理的视角看宇宙的终点*

阿瑟·爱丁顿

本文的内容是阿瑟·爱丁顿在数学协会上发表的一篇关于“宇宙的终点”的非正式讲话。他说，人们肯定首先要问“宇宙的终点是时间方向上的终点还是空间方向上的终点？”空间本身也许不存在终点：现代宇宙学认为宇宙类似于一个球体的表面，有限但无界。至于时间，热力学第二定律预言整个宇宙最终将达到一个以完全无序为标志的热平衡状态。然而，如果时间是无限的，那么宇宙粒子的每一次可能的涨落都会短暂地打破这种平衡。爱丁顿在结束语中预言了宇宙终结的实际方式：宇宙作为一个充满辐射的球不断地变大，每15亿年其大小约膨胀一倍。 [英文](#)

宇宙或者说时空是一个四维连续区，因此我们可以从很多不同的角度来讨论它的终点。毫无疑问“以数学物理的视角”来描述以下我试图展开讨论的内容绝非易事。所以我必须相当仔细地考虑这个最初的问题：宇宙的终点是时间方向上的终点还是空间方向上的终点？ [英文](#)

球面空间

我们不再寻找宇宙在空间方向上的终点。因为我们有理由相信，宇宙的空间部分具有球面结构。如果朝着空间中的任何一个方向一直走下去，我们不会到达空间的终点，也不会走到无穷远处；但是，当我们走了一段距离（并不是无法想象的远）以后，我们发现自己又回到了原来的出发点，相当于“绕了宇宙一圈”。我们把具有这种特性的连续区说成是有限但无界。球的表面即为有限无界二维连续区的一个例子；我们生活的三维空间被认为具有同样的连通性，但是由于比二维空间多出了一个空间维度，这使得我们很难用图形把这样的三维连续体表示出来。如

果我们试图画出一个三维球面空间的话，我们必须记住，只是这个三维球面对应于我们的三维空间；而这个球面的里面和外面都是我们虚构出来的，因而并不与现实的宇宙相对应。 [英文](#)

最近，主要通过勒迈特教授的工作，我们已经获知，我们生活的这个三维球面空间正在快速地膨胀着。事实上，如果我们想环绕宇宙空间一周而回到出发点的话，我们的行进速度必须要比光速还快；这是因为我们在路上行进的同时，我们前面的路途也在变长。就好像参加了一场终点线向前移动得比运动员跑步速度还快的赛跑一样。想象一下恒星和星系都镶嵌在一个橡胶气球的表面，而这个气球正在持续不断地膨胀着；这样，如果不考虑恒星和星系各自的运动以及它们之间的万有引力，这些天体之间的距离将由于宇宙空间的膨胀而变得越来越大。由于旋涡星云彼此相距很远，以至于它们几乎不会受到相互作用的引力影响，因而它们的形状很可能就体现了宇宙膨胀的效果。几年前我们就已经知道它们正在迅速地相互分散远离，我们可以通过测量它们之间的退行速度来推算宇宙的膨胀速度。 [英文](#)

天文学数据表明宇宙空间最初的半径大约为12亿光年。要知道，远至几百万光年的天体实际上已经被我们观测到了，所以12亿光年也并非是不可想象的距离。在那种尺度下，宇宙中物质间相互作用的引力刚好可以把物质聚合在一起与宇宙空间的膨胀趋势相平衡。但是这种平衡并不稳定。于是宇宙开始膨胀，最初膨胀得比较慢；但随着物质之间的距离越来越远，它们之间的引力也越来越小，以至于越来越没有办法抑制宇宙的膨胀。我们不知道宇宙现在的半径，但我估计当今宇宙的半径应该至少是最初半径的10倍。 [英文](#)

现在，我们的计算结果依赖于旋涡星云间分离速度的天文观测数据。但是我相信，我们也能从理论上顺利地得出不依赖天文观测数据的相同计算结果。从旋涡星云的退行速度我们不但可以推算出宇宙最初的尺度，还可以估算出宇宙总的质量，进而得到宇宙中总的质子数。我得出的宇宙中的总质子数为 7×10^{78} 或 14×10^{78} 。我相信这个数值与静电力和引力的比值有密切的关系，并且只与这个比值的平方相差一个常数因子。如果 F 是质子和电子之间的静电力与万有引力的比值，我们得到 $F^2 = 5.3 \times 10^{78}$ 。理论上我们有理由相信宇宙中的粒子总数是 αF^2 ，其中 α

是一个简单的几何因子（也许和 π 有关）。可能不久我们就能得到 α 的理论值，从而给出宇宙膨胀速度的观测值同静电力与引力的比值之间的完整关系。 [英文](#)

时间的指示牌

我不能继续讨论跟空间有关的问题，而必须开始讨论与时间有关的内容了。宇宙在空间上是闭合的，但是在时间尺度的两个方向上却都是开放的。从“这里”朝着空间中的任意方向出发，最后我们都会回到“这里”；但是从“现在”出发，无论是向着未来还是向着过去前进，我们将永远不可能再回到“现在”。在这里并没有弯曲的时间回路能把我们带回到原来出发的时刻。从数学上说这种差别是由记号 $\sqrt{-1}$ 造成的，正如闭合椭圆和开放双曲线之间的区别也是由这个记号造成的一样。 [英文](#)

于是，如果我们要找寻宇宙的终点——其实并不是终点，而是一种永无休止的持续，那么我们就必须从时间的两个方向中选一个作为开始的方向。但是我们如何决定应该选取哪一个时间方向呢？这是个很重要的问题。想象一下你处在时空中的某个陌生的部分，在那里你不会受到常规标志或传统参考标准的影响。但是那里应该有一个时间的指示牌，一边写着“通向未来”，而另一边写着“通向过去”。我要做的第一件事情就是要先找出这个指示牌，否则一旦我弄错了方向，那么无疑，我还是会把你们带到“宇宙的终点”，不过这个“终点”更通常地是被描述为宇宙的起点。 [英文](#)

在日常生活中，我们的意识充当了时间的指示牌。或者更准确地说，我们的意识根本不关心所谓的时间指示牌；但是无论什么地方，在紧急情况下意识总是朝着某一个特定的方向行进思考，而物理学家也温和地接受了意识的引导并把它行进方向标记为“通向未来”的方向。这里有一个重要的问题，意识在选择它的行进方向时是否也受到物理世界中的某种事物的影响？如果确实如此，那么我们应该能够直接找出究竟是物理世界中的什么因素使得有意识的人类认为时间是沿单向车道行进的。有观点认为“时间的流逝”只是一种主观的想法而不是物理世界中真实存在的现象。按照这个观点，物质世界中过去和未来的区别只不过相当于左和右之间的区别而已。事实上我们的经验显示时空就像一组电影

胶片，它总是按照某种特定的方向放映，但这并不是由胶片（物理时空）本身的性质或特点所决定的，而是与胶片插入放映机的方式（意识）有关。这种观点认为，把事物储存到我们意识中的方式使我们认为时间具有单向性：

“大自然给我们配备了这样的意识思维方式
使得我们永远不能倒退”。 英文

如果以上的观点是对的，那么在我们关于物理世界的图像中就应该抛弃“时间的流逝”这种观点。就像我们放弃旧的时空观以及其他对周围事物观察得到的个人看法一样，我们必须抛弃事物是动态呈现的这种观念，因为这并不是世界本身的性质而只是我们人类在认识物理世界时引入的一种人类特有的理解方式。我们要特别注意的是，如果真是这样，那么我们就不能先入为主地认为“过去到未来”的呈现比“未来到过去”的呈现更正确或更重要。当然，我们也必须放弃进化论，或者至少要同时建立一种具有同样重要性的反进化论。 英文

如果有谁坚持时间的行进具有单向性这种观点，我没有任何办法说他是错的。我只能对他说：“你是一个致力于把一个真实均衡的世界观灌输给年青学生的老师。但是你所教授的（或没有阻止你的同事去教授的）是完全片面的进化论学说。你并没有告诉学生进化论只是单纯事实的罗列，而是让他们认为似乎从混乱无序到完美有序的过程才是重要的，才真正会是鼓舞人心的。你这样做其实是不诚实的；你应该把反进化论也放在同样重要的位置并讲述从未来到过去的演化过程。你应该向他们展示：现今自然界存在的丰富多彩的生命形态是如何反进化到越来越不适合生存，直到古生代最原始的形态的；自然界是如何从太阳系反进化成混沌的星云；以及，随着从未来到过去的时间进程，自然界是如何选择了一个充满问题的宇宙，而这些问题并不是宇宙本身的构造不好，总而言之，最初的宇宙是一团糨糊。” 英文

熵和无序度

撇开意识的引导性不谈，我们已经发现在物理世界里有可能找到一种时间的指示牌。这个指示牌具有非常奇特的性质，当然，我还不敢说

这个指示牌的发现与当年在宇宙中发现客观的“时间流逝”有一样的重要性。但是不管怎样，这个指示牌可以用来区别过去和未来，而空间上的左和右却没有相应的客观区分。我们可以用某种称为熵的可测量量来标志这种时间方向上的差别。假设有一个孤立的系统，我们在两个不同的时刻 t_1 和 t_2 分别测量它的熵 S 。因为意识这个概念在数学物理领域里并不是可靠的证据，所以我们想在不靠意识直觉的情况下知道 t_1 究竟比 t_2 早还是晚。这里用到的规则是：熵越大，时间越晚。在数学形式中为：

$$dS/dt \text{总是大于零。}$$

这就是著名的热力学第二定律。 [英文](#)

熵是个很特殊的概念，与经典物理学常用的概念很不一样。我们可以把熵简单地描述为：熵是衡量系统无序性的物理量。于是，根据熵这个时间的指示牌，我们得到了这样的规律：从过去到未来，无序性是增加的。物理学发展的最奇妙的特点之一就是：多年来，与其他常规的分析方法一样，我们对于熵的认知一直都在悄悄地发展着。直到最近，熵在科学研究中仍只是“居于次要位置”。由熵可以很方便地得到实用的结果，但并不能由此表明人们对熵有了深刻的洞察力。不过现在熵正在谋求更大的发展，并且我认为，毫无疑问，它最终会超过它的对手。

[英文](#)

这里还需要强调几个重要的地方。首先，世界上没有其他独立的时间指示牌；所以如果我们不信任或者“通过辩解来消除”熵作为时间指示牌的这个性质，那么物理学关于过去和未来的差别也会随之消失。第二，检验熵的实验结果应该都是一致的；宇宙中任何地方的孤立系统都应该给出相同的时间方向。第三，在进行这类实验时，我们必须保证我们的系统是严格孤立的系统。进化论告诉我们，随着时间的推移，越来越高的有序系统产生了；但是这与整体上有有序性的减少并不矛盾。这在一定程度上是有序性的定义问题；从进化的角度看，需要注意的是有序性的质而非量。但无论如何，有序性很高的系统是通过吸取其他与之接触的系统的有序性来实现的。一个人从过去到未来总是变得越来越有序，至少他自己愿意这么认为。但是如果我们使他成为一个孤立的系统，即切断他的饮食和空气供应，那么他很快就会达到一种大家都认同

的“无序状态”。 [英文](#)

系统可能达到完全的无序状态，我们称之为热力学平衡态。此时，熵不能再继续增加了，而热力学第二定律又不允许它减少，于是熵就只能保持为一个常数。这时，我们的时间指示牌也消失了，因而对于这样的一个系统，时间变得固定不动了。但这并不表示时间不存在；时间仍然像空间一样存在并延续着，但是它已经不再具有任何单向性了。或者说，单行道仍然存在，但不再有汽车在上面行驶了。 [英文](#)

让我们回到时间指示牌的讨论上来。通过前面的讨论我们已经知道，无序性是不断增加的。虽然总的有序性正在减少，但是宇宙中的某些部分却展示出越来越高的特殊有序性；这就是进化现象。但是这些有序的系统最终会被不断增加的机遇与混沌所吞没，然后整个宇宙会达到一种完全无序的状态，即变成热力学平衡态下的一堆毫无特征的均匀物质。这就是宇宙的终点。时间仍然会永远地延续下去，可能没有尽头。但是时间的这种延续没有了明确的意义。很明显，在热力学平衡态即将到来之前，物理世界中已经不存在意识了， dS/dt 也成为零，再也没有一种指示牌能告诉我们，哪个时间方向通向未来，而哪个又是通向过去的。 [英文](#)

时间的起点

如果我们朝着“时间流逝”相反的方向，即朝着过去的方向看，我们将会发现更加有趣的现象。当我们沿着“时间流逝”的方向往回走时，会发现宇宙的有序性越来越大。如果我们一直不停地走下去，就会到达一个物质和能量的有序度都为允许的最高限的时刻。这时，再想进一步走下去已经不可能了。我们已经来到了时空戛然而止的终点——只不过我们通常称之为“起点”。 [英文](#)

在这里的讨论中我没有“涉足哲学”的意思。我并不认同哲学中那些与现在自然界秩序的起点有关的概念。我只是想说明物理规律中现有的基本概念使我们陷入了困境。我没有办法解决这个矛盾；也不能预料未来科学的发展能否避开这个矛盾。这个矛盾是这样的：考虑我们周围的物质，我们发现它们远不是“原子的偶然集合”。现有的物理理论所描述

的物理世界图像表明，这些单个元素的分布情况是偶然出现的概率仅仅是10的10次方的10次方分之一。有人喜欢把这种现象称之为宇宙意图或设计的非随机特性；但是，我要把它称为不受约束的反概率性。在物理学领域内，我们不愿意承认反概率性在我们所研究的包含数以十亿的原子和量子系统的相互作用中发挥了作用；而且实际上我们所有的实验结果也证实了所有这些现象都是由随机定律决定的。于是，我们就可以把反概率性从物理定律（微分方程）中剔除了。因为它总要出现在物理框架中的某个地方，所以它会很自然地在方程的边界条件里再次现身。通过把它置于我们现有的物理问题的范围之外，我们幻想着我们已经摆脱了这个困难。只有当我们中的某些人被误导着试图穿越几十亿年的时间回到过去时，我们才会发现被我们剔除的所有反概率性现象都堆在那里像一堵高墙一样形成了一个不可逾越的边界，这即是时间的起点。

[英文](#)

目前已经有人提出了一种可以解决以上矛盾的方法，这个方法似乎还得到了一些科学工作者的支持。然而，我不同意那种解释，因为我觉得它是站不住脚的，并不是因为我想让这个矛盾继续存在下去。我更愿意去找一个确切的着眼点，但是我确信现在鼓吹的着眼点其实是个死胡同。我必须首先回应对我的一些小的批评意见。

[英文](#)

有时，我会因为没有在我所讨论的内容中充分强调熵是概率性而非确定性的物理量而受到批评。如前所述，如果我们在不同的时刻观察同一个系统，那么熵较大的时刻将是较晚的时刻。严格来讲，我应该如此表述：对于一个较小的系统，上述结论正确的可能性为 $10^{20} : 1$ 。虽然我清楚地知道这个结论出错的概率是 $1/10^{20}$ ，但是，由于我在陈述上述结论时不够严谨，有些批评者仍会为此感到震惊。坦白地说：在过去的25年里，我撰写了很多文章和书籍，对物理现象做了大量的解释，恐怕我所做的各种解释中没有多少结论的出错概率会小于 $1/10^{20}$ 。在纯数学领域之外，我的结论的正误比估计更接近 $10 : 1$ ，而不是 $10^{20} : 1$ ；尽管如此，还是自负不已。我认为出错率为 $1/10^{20}$ 的结论对我们认识世界并不会有什么坏处；而我们应该稍微搁置关于出错概率的讨论。如果按照反对者的说法，这个世界上唯一能发表言论的就只可能是纯粹的数学家了。

[英文](#)

涨落

我前面所说的着眼点依赖于概率的涨落。我们考虑一群随机运动的粒子，随着时间的推移它们会经历任何可能的状态，所以只要我们等待足够长的时间，即使是最有秩序的、概率上最不可能的状态也会偶然出现。当宇宙达到完全的无序状态（热力学平衡态）后，时间仍然会无限地存在，宇宙中的元素将有机会反复经历各种可能的状态。如果我们观察足够长的时间，我们会发现，系统中一些原子所处的状态结构可能会偶然地与我们现在这个空间中的原子一样；同样偶然地，原子所组成的系统中的某一个系统出现的声波将可能与我口中现在发出的声波一样；而不管你是处于清醒还是昏昏欲睡的状态，这些声波都将去冲击由其他原子所组成的偶然与你的耳朵类似的系统。这个模拟的数学协会报告会将会在时间 t 达到无穷大之前重复很多次，实际上是无穷多次。别问我是否期望你们相信这些真的会发生。‡ [英文](#)

“逻辑就是逻辑，这就是我所说的全部。” [英文](#)

因此，当宇宙到达热力学平衡时，熵就会稳定地处在它的最大值上，除非出现一个千载难逢的极小的概率，使得熵从最大值落到明显比最大值小的值。这个涨落消失之后，要等很长时间才会碰巧发生下一次涨落。尽管也许要等 10^{10} 次方的 10^{10} 次方年的时间，但是不用担心，我们拥有无限延续的时间。这种涨落的大小并没有什么限制，如果我们等待足够久，也许我们可以碰上一次大的涨落，使宇宙远离热力学平衡态，变成和我们现在这个宇宙一样的状态。如果我们等候更长的时间，其间会有数不清的类似的大涨落发生，也许还会有一次较大的涨落使宇宙远离热力学平衡态，变回到一秒钟以前的状态。 [英文](#)

有人提出，我们现在正处在某个涨落的下坡过程中。这种提法存在令人兴奋的微妙之处。我们的宇宙刚好处在涨落的下坡过程而非往上的爬坡过程，这是一种巧合吗？完全不是。就物理世界而言，我们已经定义了时间的方向为有序度减少的方向，因此，无论我们站在山坡的哪一边，我们的指示牌都是指向下坡的。事实上，在这个理论里，总的来说时间的流逝并不是时间本身的性质，而是我们所处的那个涨落的山坡的性质。尽管这个理论假设宇宙包含了一个极不可能发生的概率事件，但

同时该理论却提供了无限长的时间使得最不可能发生的概率事件最终总能发生。无论怎样，我个人觉得以上的说法是不合理的。 [英文](#)

如果我们把一壶水放到火上，这壶水有可能结冰吗？如果一个人把一壶水放到火上无限长的时间，某一天这个人可能会惊讶地发现，他壶里的水居然结冰了。但这类事情不可能发生在我身上。即使将来有一天这种事情真的在我眼前发生了，我也不会用上面那样的方式去解释它。我宁愿相信这是一个魔鬼干的，而不是小概率事件发生了；而这样做的时候，我总该更像是一个理性的科学家吧。我现在之所以不相信魔鬼会干预我的烹调事务或者其他事情，是因为日常经验使我相信自然界会遵循一定的统一性，即物理定律。我相信这些定律是因为它们已经被反复验证过。当然，也有可能所有这些用来验证物理定律的实验一开始就恰好满足这些定律只是一种巧合。这或许是个难以置信的巧合，但是我相信这种巧合不会像我壶里的水发生结冰的巧合那样难以置信。一旦这种事件发生了，而我又找不到其他合适的解释，那么我只能在以下两种极为难以置信的巧合之间做出选择：(a) 这个世界上并不存在物理定律，迄今为止观察到的一致性仅仅是巧合。(b) 这个事件是符合物理定律的，只不过难以置信的巧合事件发生了。我更愿意接受前一种解释，因为数学计算的结果表明它的可能性更高一点。相比于违反物理定律而言，我把难以置信的巧合事件的发生看成是更加糟糕的事情；因为我之所以接受存在于自然界中的物理定律只是因为我相信难以置信的巧合事件不会发生——至少在我有生之年不会发生。§ [英文](#)

同样，如果逻辑上预言在 $t = \infty$ 之前仅仅是由于原子的随机排列而出现了个模拟的数学协会的报告，那我要说的是，我不能接受这就是今天 $t = 1931$ 年的这个数学协会报告会的理由。我们必须小心这一点，因为这里有个不小心就容易陷入的圈套。在 $t = -\infty$ 到 $t = +\infty$ 之间，1931年并不是一个完全随机的时间。我们不能因为在 $t = -\infty$ 到 $t = +\infty$ 之间只是在第 $1/x$ 个时间里有一个与今天的数学报告会一样的涨落发生了，就说在1931年里发生这种涨落的概率是 $1/x$ 。从我们现在的讨论情况来看，1931年的重要性就在于在这段时间里宇宙中出现了能够思考宇宙以及它的涨落的人类。现在我认为有一点是很清楚的，就是人类不可能在处于热力学平衡态下的宇宙中生存。要让生物能够生存下去，

宇宙就必须在很大程度上偏离平衡态。因此，对于涨落论的支持者来说，不对在10的10次方的10次方年这段时间中发生涨落的概率比数学物理学家成长和存在的最小概率还小的情况进行说明是完全合理的。这就大大缩小了x的值，但是问题仍然存在。最初的假设应该是这样的（除非我们承认某些状态在宇宙的结构中不可能发生）：几乎可以肯定地说宇宙在给定的任一时间都将近似处于最无序的状态。改进后的说法是（除非我们承认某些状态在宇宙的结构中不可能发生）：几乎可以肯定地说有数学物理学家存在的宇宙在给定的任一时间都将处于最无序的状态，而这个状态也适合人类的生存。我想，我们已经很清楚地看出以上两种说法都是站不住脚的。于是我们被迫接受反概率论；而对待它的最好办法显然是，正如之前所说过的，把所有反概率性现象整理在一起并堆积在时间的起点上。 英文

熵这个指示牌和被称作“流逝”或“发展”的时间动态特征之间的关系导致了一些非常困难的问题，在这里我不可能做详细的讨论。其中的困难之处在于熵这个指示牌似乎和我们预期的时间标记非常不同。我需要强调的是，除了意识以外，熵的增加是我们发现时间具有单向性的唯一线索。曾经有人向我提出一个粗鄙的问题：一个电子（它没有意识）是如何记住时间的流向的？为什么它不会无意中改变方向，即，朝向时间的另一个方向？它需要事先计算好朝哪个方向熵会增加，然后再决定往哪个方向前进吗？我倾向于认为电子确实会作这样的判断。对一个电荷来说，朝相反的时间方向意味着它的电荷符号要发生变化。所以，如果一个电子错误地选择了时间方向，那么它就会变成一个正电荷。这跟狄拉克博士在以电子波动方程为基础进行数学计算时碰到的一个麻烦是一样的，在他的计算里电子真的会走错方向。就像狄拉克所发现的，在一次碰撞之后，电子有一定的概率可以改变电荷的符号。你必须明白的是，这仅仅是数学的计算结果，并未在现实生活中发现。之所以是这样，我认为似乎有很合理的理由可以解释。假设我们考虑一个最多涉及四个电荷的数学问题，这个问题是任何一个计算器都能够处理的。于是，其中一个倒霉的电子不得不通过观察其他三个电荷的有序性来判断时间从过去到将来的流向。很自然，当我们只考虑三个电子的情况时，很容易发生偶然的巧合使得电子弄错方向；所以电子有很好的机会可以因为弄错了时间的方向而变成一个正电荷。但是在现实实验中，我们所

用的仪器会包含几十亿个粒子——多到足够让电子准确地确定出时间的方向。狄拉克理论预言的情况从来就没有发生过，因为与之相适的问题从来没有出现在现实世界中。如果将狄拉克理论应用于只有四个电子的宇宙中，那么经过分析很可能会给出这样的结论：在这个系统中不会存在一个稳定的单向的时间方向，奇特的事情会不断地发生，而这些在我们这个包含了约 10^{79} 个粒子的真实宇宙中是完全不可能发生的。

英文

海森堡原理

如果我们不考虑不确定性原理的话，那么我们对时间的讨论将是不完整的。这个原理是海森堡在1927年用公式表达出来并已得到一致认可的。人们已经意识到理论物理学正慢慢地偏离确定性这个基础；海森堡不确定性原理对人们的思维产生了巨大的冲击，因为这个原理作为物理世界的基本定律实际上认为未来理应具有一定程度上的不确定性或不可预测性。相比于经典物理学，这种观念上的转变使得时间的进展具有了更加真实的意义。每一个瞬间过后，世界都可能增添一些新事物——这些事物不可能单纯使用数学方法从过去已经发生的事件中推测出来。

英文

确定性的观点占主导地位至少有两个世纪了，确定论认为如果我们知道了某个时刻宇宙状态的完整数据，比如说1600年第一分钟的完整数据，那么单纯的数学推算就可以告诉我们这个世界以前是什么样子以及未来将会是什么样子。未来是由现在所决定的，因为一个微分方程的解由边界条件决定。要理解这个全新的观点，我们必须意识到我们一开始提出的“完整数据”这个概念是存在回避问题实质的风险的。而我们对物理世界的所有认识都是推论性的。我的钢笔并不是作为一个在物理世界中存在的物体使我直接认识到的；我是通过从笔上反射进我眼睛里的光以及握笔时在我肌肉中传播的压力波等感知它的存在和性质的。

英文

我们对过去事物的感知也遵循着完全一样的模式。就像现在我可以透过我的视觉感受去推断一个客观的物体，即我的钢笔一样，我也可以从患上麻疹这个情况推断出几天前应该受到了感染。如果我们完全依照

这个规律，就可以就1930年已经发生的全部事件去推断在1600年使它们发生的原因。乍一看似乎这些推断出来的原因与钢笔（也是一种推断出来的原因）的存在状态一样对我们认识物理世界具有同样重要的作用。于是确定论者们认为这令我陷入了进退两难的境地。如果某个科学工作者在1600年的世界中四处探寻并且恰好找到了这些事情的起因，那么他就有完整的数据来准确地预测1930年发生的事情；如果他做不到，那么他肯定没有完全认识1600年的宇宙，因为这些起因跟我们在其他推论过程中得出的起因一样都是些物理实体。 [英文](#)

我还需要继续说明他们是如何为了回避问题的实质而武断地规定哪些内容应该被视为是1600年的世界的完整数据，而不考虑那时是否存在可以想象的方式去获取这些数据。海森堡发现（至少在包括整个原子物理学和电子理论的广泛物理现象中），按照自然界的规律，在我们支持确定论的朋友们所需的数据中，只有一半有可能被1600年的研究者通过不懈的努力收集到，而对这一半数据的完整认识将使我们自动失去了得到另一半数据的机会。这是个很奇怪的约定，因为你可以选择要了解哪一半数据；你可以知道任何一半的数据，但就是不能同时知道全部的数据。或者你也可以做出妥协而选择不完全地知道这两个一半的全部数据，即有不确定的部分。这个物理规律是确定的：数据是成对出现的，你对一对数据中的一个测量得越精确，则对另一个的测量结果就会越不精确。 [英文](#)

当然，想要预测未来，全部数据的两个部分都是必要的，但是如果我们谨慎地选择预测的对象，我们还是可以做出一些可靠的预言的。例如，不确定性原理不会对我预测未来一年蒙特卡洛轮盘赌上的数字零出现的次数造成影响，这个次数大概是小球总的旋转次数的 $\frac{1}{37}$ 。实践证明，所有物理学和天文学上的成功预测都是通过这种取平均的办法来消除未来的内在不确定性的。 [英文](#)

作为一个例证，让我们来考虑一个最简单的预测。假设我们有一个粒子，例如电子，没有受到任何扰动而做匀速直线运动。如果我们知道它现在的位置和速度，那么预测它未来某个时刻的位置是一件很简单的事情。海森堡不确定性原理告诉我们，位置和速度是结成对的数据；也就是说，我们可以无限精确地知道它的位置，也可以无限精确地知道它

的速度，但是我们就是不能同时精确地知道这两个量。所以我们在试图准确预测这个粒子未来某个时刻对应的位置时遇到了困难。如果我们愿意的话，我们可以观察这个粒子现在时刻和未来时刻的精确位置（因为它们不是结成对的数据），然后计算出这段时间的平均速度。假如当我们由这个平均速度和最初时刻的位置来计算未来时刻的位置时，我们发现结果完全正确，于是我们成了真正的预言家——其实只是事后诸葛亮。

英文

这个不确定性原理已经完全融入了现代物理学，在波动力学中的确可以认为在电子的位置和速度之间就表现出了那种“相干关系”。由于这种相干关系，同时精确地知道电子的位置和速度是与以上的物理图像相矛盾的。因此，按照我们现在的观点，缺少预测未来所需数据中的一半算不上是信息不灵通；数据不完整是因为在我们做出预测之前它们并不存在。它们是在我们的测量行为发生之时才出现的。

英文

我认为为了充分说明我的主题，我应当用一个预言来作为对宇宙终点可能会是什么样子这个问题的总结。我承认我并不十分情愿回答这个问题。我甚至想，既然我刚才已经解释了未来是不可预测的，我就可以以此为借口拒绝回答这个问题。但恐怕有人会说，你这个借口太勉强，你所需要做的只是计算一下平均值，而那种类型的预言并不违背不确定性原理。过去我们认为宇宙中的所有物质最终会聚集到一起变成一个温度均匀、密度极大的圆球；但是球面空间的学说，尤其是由此得到的宇宙膨胀的最新结论改变了以前的看法。现在还存在一两个未得到解决的问题，这使得我不能得出明确的结论，所以我在这里只是给出其中的一种可能性。大家普遍认为物质会慢慢地转变成辐射。如果是那样的话，整个宇宙就会变成一个不断膨胀的充满辐射的球，辐射会变得越来越弱，相应的波长也变得越来越长。大概每过15亿年，宇宙的半径就会增加一倍，宇宙的大小将会以这种几何级数的增长方式永远地膨胀下去。

英文

（沈乃澂 翻译；张元仲 审稿）

* 这篇文章来自爱丁顿于1月5日在数学协会上发表的讲话。

† 这个结果的不确定性与在有限无界的空间中计算粒子数有不可分割的联系。因为我们无法分辨这些质子到底被计算过一次还是两次。

‡ 我希望“宇宙膨胀”说会阻止它的发生。

§ 毫无疑问，“极不可能”发生的巧合会在我们面前发生，只是这种巧合事件的发生概率与我们在此讨论的巧合事件有完全不同的数量级。

Obituary

In the nineteenth century, the propagation of light raised considerable difficulty in the minds of scientists. As Maxwell had demonstrated, light consists of electromagnetic waves, but people found it difficult to visualise the occurrence of wave motion in an entirely empty space. So there became established the idea that light travels through an insubstantial (that is, massless) medium called the lumeniferous ether. Albert Michelson and his chemist colleague Edward Morley carried out an experiment using a specially constructed interferometer designed by Michelson to compare the velocity of light in two directions perpendicular to each other. The outcome of the experiment suggested that the behaviour of light in the two perpendicular arms of the equipment was identical, thus throwing doubt on the whole concept of the lumeniferous ether—a point from which Einstein's Special Theory of Relativity was founded in 1905. [中文](#)

Prof. A. A. Michelson, For Mem. R. S.

WE much regret to announce the death, which occurred on May 9, of Prof. A. A. Michelson, the distinguished physicist of the University of Chicago. Prof. Michelson was probably best known for his wonderful experimental work to detect any effect of the earth's rotation on the velocity of light. At the end of 1929, he resigned his position at the University of Chicago and went to Pasadena, where he

proposed to carry out further work on this subject, and it is reported that preliminary measurements have already been made. Prof. Michelson had worked previously at Mount Wilson Observatory, Pasadena, and a brief account of repetitions of the famous Michelson–Morley experiment, as it is generally called, with a diagram of the apparatus, was contributed to *Nature* of Jan. 19, 1929, by him and his collaborators. The results then obtained showed no displacement of the interferometer fringes so great as one-fifteenth of that to be expected on the supposition of an effect due to a motion of the solar system of three hundred kilometres per second through the ether. Since then, Prof. Michelson has been awarded the Duddell Medal for 1929 of the Physical Society of London for his work on interferometry.

[中文](#)

In *Nature* of Jan. 2, 1926, we were fortunate in being able to publish, as one of our series of “Scientific Worthies”, an appreciation of Prof. Michelson and his work by Sir Oliver Lodge. We print below extracts from that article. [中文](#)

“Albert Abraham Michelson was born in Strelno, Poland, on Dec. 19, 1852. In 1854 his parents migrated to the United States. After emerging from High School in San Francisco, young Michelson was appointed to the Naval Academy, from which he graduated in 1873, and two years later became instructor in physics and chemistry under Admiral Sampson, continuing this work until 1879. After a year in the Nautical Almanac Office at Washington, Michelson, now an ensign, went abroad for further study at the Universities of Berlin and Heidelberg, and at the Collège de France and the École Polytechnique in Paris. Upon his return to the United States in 1883 he became professor of physics in the Case School of Applied Science, Cleveland, Ohio; whence, after six years, he was called to Clark University, where he remained as professor until 1892, when the University of Chicago opened its doors. Prof. Michelson went to this new institution as

professor of physics and head of the department. In June 1925 he was honoured by being appointed to the first of the Distinguished Service Professorships made possible by the new development programme of the University. [中文](#)

“It was while he was at Cleveland that Prof. Michelson collaborated with Prof. Morley in their joint experiment; and it may have been for the purpose of that experiment that he invented his particular form of interferometer, with the to-and-fro beams at right angles. Later, he applied it in Paris to the determination of the metre, with an estimated accuracy of about one part in two million. [中文](#)

“During the War, Prof. Michelson re-entered the Naval Service with the rank of Lieutenant-Commander, giving his entire time to seeking new devices for naval use, especially a range-finder, which became part of the U.S. Navy Equipment. [中文](#)

“A Nobel Prize was awarded to Prof. Michelson in 1907, the first American to get one for science; and the Copley Medal, the most distinguished honour of the Royal Society of London, was awarded him in the same year. [中文](#)

“The gold medal of the Royal Astronomical Society was presented to Prof. Michelson on Feb. 9, 1923; and the compact exposition of the reasons for that award, by the president, Prof. Eddington, on that occasion will be found in *Nature*, vol.111, p. 240. [中文](#)

“Michelson touched on many departments of physics, but in optics, the highest optics, he excelled. In this subject he can be regarded as the most fertile and brilliant disciple of the late Lord Rayleigh, for his inventions are based on a thorough assimilation of the principles of diffraction, interference, and resolving power; and his great practical achievements are the outcome of this knowledge. Michelson seemed to have a special instinct for all phenomena connected with the interference of light, with a taste for exact measurement surpassed by

none in this particular region. The interferometer with which he began became in his hands much more than an interferometer. He applied it to the determination of the standard metre in terms of the wave-length of light, with exact results which will enable remote posterity millions of years hence to reconstruct, if they want to, the standard measures in vogue at this day. He applied it also to analyse the complex structure of spectrum lines, and with remarkable completeness to determine the shape and size of invisible objects, such as to ordinary vision, however much aided by telescopic power, will probably remain mere points of light. 中文

“In a magnificent paper in the *Phil. Mag.* of July 1890, Michelson suggested the application of interference methods to astronomy. He knew well that the resolving power of a telescope depended on the diameter of its aperture, and that the formation of an image was essentially an interference phenomenon; the minuteness of a point image, and therefore the clearness of definition, depending on the size of the object-glass. But he pointed out that if the aperture was limited to slits at opposite edges—so that no actual image anything like the object would be formed, but only the interference bands which the beams from the two slits could produce—a study of those bands would enable us to infer about the source of light very much more than we could get by looking at its image. For example, suppose it was a close double star, and suppose the slits over the object-glass were movable, so that they could be approached nearer together, or separated the whole distance of the aperture apart. A gradual separation of the slits would now cause the fringes to go through periods of visibility and invisibility; and the first disappearance of the fringes would tell us that the distance apart of the two components of the star (multiplied by the distance between the slits and divided by the distance of the star) would equal half a wave-length of light. The two components might be far too near together ever to be seen separately, and yet we could infer that the star was a double one; and by further attention to

the visibility curve we could infer the relative brightness of the two components and their position relative to our line of sight. [中文](#)

“Furthermore, if, instead of looking at a star, we turned the slit-provided telescope on a planet with a disc too small for ordinary measurement, the size of that disc could be estimated from the behaviour of the interference fringes produced by its light in a suitable interferometer, or by the telescope converted into one. [中文](#)

“In view of the great interest aroused by the application of this method by Michelson himself, with the aid of collaborators at Mount Wilson Observatory, Pasadena, California, and with the hundred-inch telescope established there, it may be interesting to quote here part of the conclusion of his paper of date 1890:

“ ‘(1) Interference phenomena produced under appropriate conditions from light emanating from a source of finite magnitude become indistinct as the size increases, finally vanishing when the angle subtended by the source is equal to the smallest angle which an equivalent telescope can resolve, multiplied by a constant factor depending on the shape and distribution of light in the source and on the order of the disappearance.

“ ‘(2) The vanishing of the fringes can ordinarily be determined with such accuracy that single readings give results from fifty to one hundred times as accurate as can be obtained with a telescope of equal aperture.’ [中文](#)

“ ‘If among the nearer fixed stars there is any as large as our sun, it would subtend an angle of about one hundredth of a second of arc; and the corresponding distance required to observe this small angle is ten metres, a distance which, while utterly out of question as regards the diameter of a telescope-objective, is still perfectly feasible with a refractometer. There is, however, no inherent improbability of stars presenting a much larger angle than this; and the possibility of gaining

some positive knowledge of the real size of these distant luminaries would more than repay the time, care, and patience which it would be necessary to bestow on such a work.’ [中文](#)

“There seemed little hope at that time, and certainly no reasoned expectation, that any stars, except perhaps some of the very nearest, could have discs big enough for perception and measurement even by this virtual telescope of thirty feet aperture. The possibility of giant stars came, however, above our mental horizon; and Eddington made the notable prediction that a star like Betelgeuse must be in a highly rarefied state at a tremendously high temperature, and that it would be swollen out by the pressure of light to a size almost comparable with the dimensions of a solar system, although it could not contain very much more matter than, say, two or five times our sun. His argument, in brief, is that the spectrum of a young red star like Betelgeuse shows that it cannot be radiating furiously. Why then is it so conspicuous an object to our vision? It can only be because it is of enormous size, its density perhaps a thousand times less than atmospheric air. By utilisation of the data available in the light of his theory of stellar constitution, Eddington made an estimate of the diameter of the star. [中文](#)

“So with great skill Michelson and his collaborators got the interferometer to work. After many preliminary adjustments, on Dec. 13, 1920, Dr. F. G. Pease at Mount Wilson, with Michelson’s apparatus, measured the diameter of a star for the first time, using Betelgeuse for the purpose. The interference-fringes formed by the star were observed, the object mirrors were gradually separated, and it must have been a joyful moment when, as they grew farther and farther and farther apart, the fringes at the eye end became less distinct and ultimately disappeared. The distance apart of the mirrors now, multiplied by the proper fraction, gave the angular dimensions of the star—a thing which had never before been observed in the

history of the world. An estimate of the star's distance gave its actual diameter, and confirmed Eddington's prediction! 中文

“Other stars have since been measured, and the giant stars well deserve their name. Moreover, an instrument has been put in the hands of posterity to the power of which we can scarcely set a limit in investigating utterly invisible details, both about the heavenly bodies and about atoms, by the new and powerful method of analysing the radiation which they emit. 中文

“The form of instrument adapted to the heavens is, however, not applicable to the atoms. The spectrum of atomic radiation is formed by a grating; and Rayleigh showed that the power of a prism spectroscopy is expressed approximately by the number of centimetres of available thickness of glass, which is one form of saying that, to get high definition or separating power, we must use interference depending on a great number of wavelengths retardation. Michelson perceived that the retardation principle might be employed so as to make a grating which combined with its own effect the resolving power of a prism. A slab of glass, a centimetre or more thick, might be used to give the necessary lag in phase of many thousand wavelengths, and thereby secure a definition and resolving power unthought of before. So Michelson designed the Echelon spectroscopy, consisting of thick slabs of glass, each protruding a millimetre or so beyond the other—a staircase spectroscopy—which is now a regular instrument in the examination of the minute structure of spectrum lines. 中文

“What, however, is popularly the best-known work of Michelson is the application of his interferometer to determine if possible the motion of the earth through the ether. The speed expected was of the order one-tenth-thousandth of the velocity of light; but since the journey of the light in the instrument is a to-and-fro journey—one half-beam going as nearly as possible with and against the hypothetical stream of

ether, while the other half-beam goes at right angles to that direction—the amount to be measured was not one-ten-thousandth but the square of that quantity; that is to say, the observer had to measure one part in a hundred million—no easy matter. The interferometer was mounted on a stone slab floating in mercury, and the whole observation conducted with great care. The result was zero; and that zero was used afterwards as the corner-stone of the great and beautiful edifice of relativity.” 中文

(127, 751-753; 1931)

讣告

在19世纪，科学家们对光的传播的理解仍面临着很大的困难。麦克斯韦指出，光是由电磁波构成的，但人们觉得很难想象波会在真空中传播。所以有人提出光在质量为零的以太中传播。阿尔伯特·迈克尔逊与他的化学家同事爱德华·莫雷用迈克尔逊本人设计的干涉仪测量并比较了互相垂直的两束光在传播速度上的差异。实验结果说明，光在干涉仪两个相互垂直的臂上的行为是相同的，这使人们对传光以太的概念产生了怀疑——而基于这一点爱因斯坦在1905年提出了狭义相对论。

[英文](#)

英国皇家学会为纪念迈克尔逊教授所写的悼词

我们非常遗憾地告诉大家：芝加哥大学杰出的物理学家迈克尔逊教授在5月9日与世长辞了。迈克尔逊教授最著名的工作大概要算他检测地球旋转对光速影响的完美实验。1929年末，他放弃了在芝加哥大学的职位，赴帕萨迪纳继续开展这方面的研究，据报道他已经完成了前期的测量工作。迈克尔逊教授先前曾在帕萨迪纳的威尔逊山天文台工作过，他和他的合作者在1929年1月19日的《自然》杂志上发表了有关迈克尔逊-莫雷实验的文章，他们用装置图简单再现了这个为大家所公认的著名实验。后来得到的结果表明，假设太阳系以每秒300公里的速度在以太中运动，干涉条纹的位移不会超过预期值的1/15。1929年，迈克尔逊教授因在干涉测量法方面的贡献而被伦敦物理学会授予达德尔奖章。

[英文](#)

我们很荣幸能在1926年1月2日《自然》杂志的“杰出科学家”系列介绍中发表奥利弗·洛奇爵士对迈克尔逊教授及其研究工作的评论。以下内容是我们从那篇文章中摘录出来的。

[英文](#)

“阿尔伯特·亚伯拉罕·迈克尔逊于1852年12月19日出生于波兰的斯特列罗。1854年，他随父母移居美国。年轻的迈克尔逊在旧金山读完高中后被指派到海军学院学习一直到1873年毕业，两年后他成为桑普森上将手下的一名物理和化学教员，并在此一直工作到1879年。后来他又为华盛顿的航海天文历编制局工作了一年，此时已是海军少尉的迈克尔逊走出了国门，先后到柏林大学、海德堡大学、法兰西学院和巴黎理工学校深造。他在1883年回到美国，随即成为位于俄亥俄州克利夫兰的凯斯应用科学学院的物理教授；6年后，克拉克大学邀请他担任该校的教授，他在那里一直工作到1892年芝加哥大学成立。迈克尔逊教授在这个新建的大学中担任物理学教授和物理系主任。1925年6月，由于该大学新发展规划的需要，他荣幸地被提名为首位对社会有杰出贡献的教授。

[英文](#)

“正是在克利夫兰工作的时候，迈克尔逊教授与莫雷教授合作进行了他们的实验；为完成这个实验，迈克尔逊教授发明了可以在相互垂直方向上使光线来回反射的干涉仪。后来他在巴黎用这个仪器测量了标准米，估计精度在 $1/2,000,000$ 上下。

[英文](#)

“在第一次世界大战期间，迈克尔逊教授重返海军服役，军衔为少校，他把自己全部的时间都用于研制适用于海军需要的新仪器，尤其是已经成为美国海军装备组成部分的测距仪。

[英文](#)

“迈克尔逊教授获得了1907年的诺贝尔奖，他是第一位获此殊荣的美国科学家；在同一年，他还荣获了代表伦敦皇家学会最高荣誉的科普利奖章。

[英文](#)

“1923年2月9日，迈克尔逊教授被授予皇家天文学会金奖；《自然》杂志在第111卷的第240页上刊登了皇家天文学会主席爱丁顿教授在颁奖仪式上对其获奖原因的简短说明。

[英文](#)

“迈克尔逊曾经涉足过物理学的许多领域，但他在光学领域，最前沿的光学领域所取得的成就最为突出。在这个领域中，他可以被认为是已故瑞利勋爵的所有弟子中成果最丰硕和最优秀的一位，因为他的发明是建立在透彻理解衍射、干涉原理以及分辨率的基础上的；而他在实践上的伟大成就就是能够充分运用这些知识的结果。迈克尔逊似乎对所有与

光干涉相关的现象都有一种特别的直觉，在这个特定领域中他对精确测量的判断力是无人能及的。在他眼中，自己早先发明的干涉仪远远不只是一部干涉仪。他利用干涉仪根据光的波长测定了标准米，得到的结果非常精确，可以让几百万年以后的子孙重新构建当今流行的计量标准，只要他们愿意。他还利用干涉仪分析了谱线的复杂结构，并且完美地测定了不可见物体的形状和大小，这些不可见物体对于视力正常的人来说，即使借助大倍率望远镜也只能看到几个光点。 [英文](#)

“1890年7月，迈克尔逊在一篇发表于《哲学杂志》上的优秀论文中提到了干涉法在天文学中的应用。他非常清楚望远镜的分辨力取决于其孔径的大小，而从本质上看，像的形成是一种干涉现象；点像的精确性以及与此相关的轮廓清晰度取决于物镜的尺寸。但他指出，如果孔径受到对面边缘狭缝的限制，则不能形成与物体类似的实像，而来自两个狭缝的光束只能形成干涉带，通过研究这些干涉带推出的有关光源的信息要比我们从观察图像本身得到的信息多很多。例如，假设有一对相离很近的双星，并假设物镜上的狭缝是可移动的，它们可以靠得更近，也可以相距整个孔径那么大的距离。使两个狭缝逐渐远离就能实现条纹从可见到不可见的周期变化；条纹的首次消失将告诉我们，恒星两组分之间的距离（乘以狭缝间的距离，除以双星到地球的距离）等于光的半波长。也许双星之间的距离过于接近，以至于我们从未观测到它们是分开的两颗星，但我们已经可以推测出该恒星是一对双星；通过对可见度曲线的进一步研究，我们还可以推断出双星的相对亮度以及它们相对于我们视线的位置。 [英文](#)

“此外，除了观察恒星以外，我们还可以将装有狭缝的望远镜对准一颗星盘很小、用普通测量方法难以观测到的行星，来自星盘的光在适当的干涉仪中或由望远镜改装成的干涉仪中形成干涉条纹，根据这些条纹的变化情况可以估算出星盘的尺寸。 [英文](#)

“迈克尔逊本人把自己的方法应用于天文学领域激起了人们极大的兴趣，他得到了加州帕萨迪纳威尔逊山天文台的工作人员的帮助，并使用了安装在那里的孔径可达百英寸的望远镜，考虑到这一点，在此引述他在1890年论文中的部分结论也许是一件有意思的事情：

“(1) 在适当条件下，如果干涉现象的产生源于有限强度光源发出的光，那么随着光源尺寸的增加，干涉现象就会逐渐变模糊，当光源所张的角度等于等效孔径望远镜所能分辨的最小角度乘上一个常数因子时，干涉现象将最终消失，这个常数因子取决于光源中光的状态和频率分布以及干涉现象消失的量级。

“(2) 通常用于测量条纹相消的方法有很高的精确度，其单次测量所得结果的精度是等孔径望远镜的50至100倍。” [英文](#)

“如果在比较靠近我们的恒星中存在着一个与太阳大小差不多的恒星，那么它所张的角度将大约是1/100角秒；而观测这么小的角度需要10米的距离，望远镜物镜的直径完全可以达到这么长的距离，这个距离对于折光仪来说也毫无问题。然而，恒星所张角度大大高于1/100角秒的情况未必不可能出现；获得这些遥远发光体实际尺寸的有用信息是有可能的，而且值得人们投入时间、精力和耐心，而完成该项工作也需要这样的投入。” [英文](#)

“在当时几乎无法希望，当然也没有理由期望，恒星的星盘能够大到足以感知和测量的地步，即便是采用孔径为30英尺的虚拟望远镜，不过一些最接近我们的恒星也许可以除外。然而，可能存在巨星的想法进入了我们的视野；爱丁顿提出了那个著名的猜想，即像参宿四这样的恒星必然会处在极高温度下的高度稀薄状态，它在光压的作用下将膨胀到几乎与整个太阳系相近的尺寸，尽管它含有的物质不可能比太阳上的物质多多少，也就是太阳的2倍或5倍。简言之，他的结论是，从一颗类似于参宿四的年轻红巨星的光谱判断，它不可能在强烈地辐射能量。然而为什么我们很容易看到这样的天体呢？原因只能是它具有特别大的尺寸，而它的密度可能仅为空气密度的1/1000。爱丁顿利用根据自己提出的恒星构造理论得到的数据估算出了这个恒星的直径。” [英文](#)

“于是迈克尔逊和他的合作者们开始熟练地操作干涉仪进行研究。1920年12月13日，在经过了多次调试之后，皮斯博士在威尔逊山上用迈克尔逊的装置首次测出了一颗恒星的直径，测量的恒星正是参宿四。可以观测到由恒星形成的干涉条纹，令物镜逐渐分离，当物镜之间的距离越来越远时，肯定会出现那个令人欣喜的时刻，目端的干涉条纹逐渐

变模糊直至最终消失。这时用物镜之间的距离乘以一定的比例就得到了这颗恒星的角度大小——这在世界历史上还从未被人观测到过。根据对恒星距离的估计可以算出它的实际直径，从而验证了爱丁顿的预言！

英文

“后来又测量了其他的恒星，发现那些巨星果然具有很大的体积。再者，这种已经传到后人手中的仪器功能非常了得，在用这种功能十分强大的新方法分析天体和原子发出的辐射时，我们简直不知道它是否有做不到的事情。

英文

“然而，适用于观察天体的仪器规格并不适用于原子。原子辐射光谱是由光栅得到的；瑞利发现棱镜分光镜的分辨率可近似表示为玻璃可用厚度的厘米数，也就是说，为了达到更高的清晰度或分辨率，我们必须用到与大量波长延迟有关的干涉现象。迈克尔逊意识到也许可以利用延迟原理制成一个光栅，这个光栅既具有自己的特殊功用又具有棱镜的分辨能力。也许可以用一片厚度为1厘米或更厚的玻璃实现所需的几千个波长的相位滞后，由此获得以前无法想象的清晰度和分辨率。于是迈克尔逊设计出了由厚玻璃片组成的阶梯光栅分光仪，每一个玻璃片都比另一个约长出1毫米，这种阶梯状的分光镜现在已经成为检测谱线精细结构的常规仪器。

英文

“然而，大家普遍认为迈克尔逊最著名的成就是利用干涉仪来测定地球在以太中的运动，如果这种运动是存在的。人们预期其速度的数量级大概为光速的 $1/10,000$ ；但由于光在仪器中所走的路线是连续往返的，有一半的光束可以尽可能地与假想的以太流方向一致或相反，而另一半光束的行进方向与此垂直，测量出来的结果不应该是 $1/10,000$ ，而应是 $1/10,000$ 的平方；换言之，观测者要测量的是这个量的 $1/100,000,000$ ——这绝非易事。干涉仪被放在浮于水银表面的石板上，在整个观测过程中的操作都非常小心。最后得到的结果是零；后来这个零成为壮观美丽的相对论大厦的基石。”

英文

（沈乃澍 翻译；张泽渤 审稿）

The Annihilation of Matter*

J. Jeans

James Jeans notes here that one of the sacred principles of science was giving way. It had been a bedrock belief of physicists for centuries that matter can be neither created nor destroyed. Yet now, he points out, it looked increasingly certain that the process by which stars generate energy could only be explained through the annihilation of matter. Evidence showed that the average star has already emitted many times its own mass in radiation. The life history of a star seemed to be a continual annihilation of its substance, as massive particles give up their energy to produce radiation. The explanation for this is now seen to come from nuclear fusion, in which mass and energy are interconverted via Einstein's $E = mc^2$. [中文](#)

THROUGHOUT the greater part of the history of science, matter was believed to be permanent, incapable either of annihilation or of creation. Yet a large amount of astronomical evidence now seems to point to the annihilation of matter as the only possible source of the energy radiated by the stars. A position has thus been reached in which the majority of astronomers think it probable that annihilation of matter constitutes one of the fundamental processes of the universe, while many, and perhaps most, physicists look on the possibility with caution and even distrust. I have thought it might be of interest to attempt a survey of the present situation in respect to this question.

The Astronomical Evidence

The astronomical argument for the annihilation of matter is based, not on the intensity of stellar radiation, but on its duration. No transformation of a less drastic nature than complete annihilation is found capable of providing continuous radiation for the immense periods of time throughout which the stars have, to all appearances, lived. For, with one conspicuous exception, to be discussed later, all available methods of estimating stellar ages are found to indicate that the stars, as a whole, have already lived through periods of millions of millions of years. 中文

Some of these methods depend on the rate of gravitational interaction between adjacent stars; for example, the velocities with which the stars move through space show an approximation to equipartition of energy, such as must have required millions of millions of years for its establishment. The individual members of the groups of stars known as moving star clusters appear to have had their courses changed by the gravitational pull of passing stars to an extent which again indicates action extending over millions of millions of years. The same is true of the orbits of visual binary stars. In each of these three cases, the clock we use has for its unit a time analogous to what is called the “time of relaxation” in the theory of gases; in this comparison the single stars correspond to monatomic molecules, and binary stars to diatomic molecules, while the disintegration of a moving star cluster provides the counterpart of the process of gaseous diffusion. 中文

These estimates of stellar ages are, of course, valid only if we assume that the changes in stellar motions and arrangements are produced solely by the gravitational pulls of other stars. Other causes are conceivable, and must indeed contribute something—pressure of radiation, bombardment by stray matter in space, or by the atoms of

cosmic clouds diffused through space. But calculation shows that the contributions from these sources are quite negligible. Indeed, when we take them into account, the discussion of stellar movements is no longer a problem of astronomy, but of physics; we have to treat the stars as Brownian “particles” in a physical medium. When they are so treated, we find that the starry medium has a temperature—in the sense in which we speak of the temperature of moving Brownian particles—of the order of 10^{62} degrees. Both individual and binary stars exhibit the equipartition of energy which corresponds to a temperature of this order, whence it is obvious that physical agencies such as pressure of radiation and atomic pressures, which are in equilibrium with far lower temperatures of the order only of 10^4 degrees, cannot have made any appreciable contributions to the establishment of this equipartition; they act as mere drags on the stellar motions, tending on the average to check their speed. [中文](#)

In a second class of binary stars, the spectroscopic binaries, the two components are so close together that the gravitational pull from passing stars is approximately the same on each, and so cannot exert the differential action which would change the relative orbits of the constituent masses. Clearly there can be no question of any approximation to equipartition of energy in the internal motions of these systems. Nevertheless, it is possible to trace a steady sequence of configurations, beginning with almost circular orbits in which the two constituents are practically in contact—this being probably the condition of a system which has just formed by fission—and proceeding to orbits which are far from circular in shape, in which the components are at a substantial distance apart. It seems likely, although not certain, that this sequence is one of advancing age; when the parent star first breaks up to form a binary, the newly formed system starts at the first-mentioned end and moves gradually along the sequence. Now observation shows, beyond all doubt, that the stars at the far end of this sequence are substantially less massive than

those at the beginning. We know the rate at which the various types of stars are radiating their mass away in the form of radiation, and from this we can calculate the time needed to produce the difference of mass which is observed to exist between the two ends of the sequence; again it proves to be a matter of millions of millions of years. Here the clock we use is the rate of outflow of radiation from a star, or its equivalent, the rate of loss of mass. [中文](#)

Against these various estimates must be set one piece of evidence which, if interpreted in the most obvious way, seems to point in exactly the opposite direction. This is, that the remote extra-galactic nebulae all show a shift of their spectral lines to the red, the amount of shift being approximately, although not exactly, proportional to the distance of the nebula. If this is interpreted in the most direct way, as a Doppler effect, the nebulae must all be scattering away from us and from one another in space, at so great a speed that the whole universe doubles its size about once in every 1,400 million years. Such a rate of increase seems quite inconsistent with the estimate which assigns ages of millions of millions of years to the stars. Calculation suggests that the original radius of the universe must have been of the order of 1,200 million light-years (Eddington), while the present radius of the universe appears to be only of the order of 2,000 million light-years (de Sitter). If these estimates could be treated as exact, we could fix the age of the universe definitely at just more than 1,000 million years, which is substantially less even than the age of the earth as indicated by its radioactive rocks. No one would claim any great degree of exactness for either of these estimates, especially the second, yet the general situation seems to forbid that the universe can have been doubling in size every 1,400 million years throughout a period of millions of millions of years. [中文](#)

Although alternative interpretations are tenable, none of them seems entirely convincing, and the present situation is extremely puzzling.

While there is obviously room for much difference of opinion, many astronomers consider it likely that some other explanation of the apparent recessions of the nebulae will be found in time, in which event the road will be clear for the acceptance of ages of millions of millions of years for the stars, as suggested by the main bulk of astronomical evidence. [中文](#)

If such ages are provisionally accepted, calculation shows that the average star has already emitted many times its total mass in radiation; in other words, the average star must have started life with many times its present mass. Indeed, the sequence of spectroscopic binaries gives us a sort of picture of the life-history of a typical star. It starts with anything from ten to a hundred times the mass of the sun, and ends with a mass comparable to, or even less than, that of the sun. It is difficult to see where the enormous weight of the newly-born star can have been stored if not in the form of material atoms, or at any rate of material electrons and protons. Thus we are led to suppose that the life-history of the star is one of continual annihilation of its substance, the electrons and protons annihilating one another, and providing the energy for the star's radiation in so doing. Such, at least, is the conjecture suggested to us by astronomy; the testing of the conjecture rests with physics. [中文](#)

Highly Penetrating Radiation

If any direct evidence of this process of annihilation is to be obtained, it seems most likely that it will be found in the highly penetrating radiation which McLennan, Rutherford, and others discovered in the earth's atmosphere at the beginning of the present century. The reason, as we shall see later, is that here, and here alone in the whole of physics, we are dealing with photons of radiation whose mass is comparable with that to be expected in photons resulting from the annihilation of electrons and protons. In the last few years, this radiation has been studied in great detail by Hess, Millikan, Regener,

and many others. Their investigations scarcely leave room for doubt that the radiation enters the earth's atmosphere from outer space; for which reason it is often described as "cosmic radiation". 中文

It was at first taken for granted that this radiation must be of the nature of γ -radiation, since its penetrating power was greater than seemed possible for any kind of corpuscular radiation. This reason is now known to be inadequate, theoretical investigations having shown that corpuscular radiation, consisting of either α - or β -particles, might conceivably possess as high a penetrating power as the observed radiation. 中文

Other arguments have, however, stepped into the breach, and show very convincingly that the radiation cannot be of the nature of either α or β radiation. The central fact is, in brief, that radiation which consisted of charged particles would be influenced by a magnetic field, whereas cosmic radiation is not. An electron or other charged particle in motion acquires magnetic properties in virtue of its motion; the faster it moves, the greater the force which a magnetic field exerts upon it. Now the penetrating power of the radiation under consideration is so great that it could only be attained by charged particles, if these were moving with very high speeds indeed. If a swarm of such particles became entangled in the earth's magnetic field, their high speed of motion would cause them to describe spiral paths coiled quite closely around the earth's lines of magnetic force, with the result that they would fall far more abundantly near the earth's magnetic poles than elsewhere. Epstein¹ estimates that for a shower of electrons to have the penetrating power of cosmic radiation, they would have to move with the energy produced by a fall through about 1,000 million volts, and has calculated that the incidence of electrons moving with this energy would be limited entirely to comparatively small circles surrounding the two magnetic poles. Actually the observed radiation falls so evenly on the different parts of

the earth's surface that no variations have ever been detected. Members of the B.A.N.Z. Antarctic Expedition² found the same intensity of radiation within 250 miles of the south magnetic pole as they had previously measured in South Australia, and as others had found in the United States, Canada, and the North Atlantic. This seems to leave little room for doubt that the radiation is of the nature of very hard γ radiation.³ [中文](#)

At first, some experiments by Bothe and Kohlhörster seemed to throw doubt on this conclusion. They had placed two Geiger counters, one vertically above the other, and found that the number of coincident discharges in the two counters was just about that which would be expected from purely geometrical considerations, if the radiation was corpuscular. Of course, the radiation which produced these ionisations was not necessarily the primary radiation which fell on the earth from outer space. Any primary radiation, as it traverses the atmosphere, is bound to produce secondary radiation of a variety of kinds, and any one of these might have been the immediate cause of the ionisation observed by Bothe and Kohlhörster. The primary radiation which first enters the earth's atmosphere might quite conceivably be electromagnetic, while the ionisation might be produced by a secondary corpuscular radiation. [中文](#)

To examine this possibility, Bothe and Kohlhörster placed a block of gold between their two counters. This naturally caused a reduction in the number of coincidences, and from the amount of the reduction it was possible to calculate the penetrating power of the radiation which actually effected the ionisations. It was found to be approximately the same as that of the primary radiation. So far, then, everything could be explained by supposing that it was the primary radiation itself which produced the ionisations in the counters, and that this was corpuscular in its nature. [中文](#)

Recently this explanation has been tested by Moss-Smith⁴ and found

wanting. He extended the apparatus used by Bothe and Kohlhörster, by mounting yet a third counter vertically below the original two, and first verified that the number of coincident ionisations in all three counters was that which their geometrical arrangement would lead us to expect. Now if the radiation which produced these ionisations were corpuscular, it ought to be deflected by a magnetic field. For example, if a sufficiently strong magnetic field were inserted between the second and third counters, the third counter ought to be entirely shielded from the radiation which had passed through the first two counters, so that the number of coincident ionisations in the first two counters would remain as before, while the number in the third counter would fall to zero. Moss-Smith found that this did not happen. Although his magnetic field had many times the strength needed to shield the third counter completely, its insertion had no effect on the number of coincident ionisations. This showed that the ionising radiation was not corpuscular, and as Bothe and Kohlhörster had already shown that the ionising radiation was probably identical with the primary radiation, it confirmed the theoretical arguments of Millikan and Epstein, which proved the primary radiation to be of the nature of γ radiation. [中文](#)

The Mode of Production of the Radiation

If the primary radiation is of the nature of γ radiation, as these arguments and experiments seem to show, its origin ought to be disclosed by its penetrating power. Such radiation consists of photons, which may be compared to bullets, all moving with the same speed—the velocity of light. Their penetrating power accordingly depends solely on their mass, and a theoretical investigation enables us to deduce the one from the other. Every photon is, however, produced originally by an atomic upheaval, and its mass is exactly equal to the decrease of mass which the parent atom experienced as the result of this upheaval. For example, if the atom was one of hydrogen and the

upheaval consisted of annihilation, the photon resulting from this annihilation must have a mass exactly equal to the original mass of the hydrogen atom, namely, 1.66×10^{-24} gm. Or again, if a proton and an electron mutually annihilate one another in any atom whatever, thus reducing its atomic weight by unity, the mass of the resulting photon must be equal to the combined masses of the proton and electron in situ in the atom, which again, except for a small “packing-fraction” mass, is equal to the mass of a hydrogen atom. [中文](#)

The most effective means of investigating the penetrating power of cosmic radiation is to sink suitable apparatus to varying depths below the surface of a lake, and observe the ionisation produced by the incidence of the cosmic rays after absorption by varying depths of water. Observations of this type have been performed with great care and skill by Millikan, Regener, and others. [中文](#)

Their results are none too easy of interpretation. L. H. Gray has shown⁵ that there is a sort of softening effect continually in progress by which the absorption of a quantum of energy produces a recoil electron, which in turn produces radiation of energy comparable to, although somewhat lower than, the energy of the original quantum. After the radiation has travelled through a certain thickness of absorbing material, the observed ionisation no longer gives a true measure of the intensity of the primary radiation which has escaped absorption, but of this primary radiation in equilibrium with all its softer secondary components. [中文](#)

When this complication has been allowed for, the ionisation curve gives the intensity of the true primary radiation which remains after passing through varying thicknesses of absorbing matter. If this primary radiation consists of a mixture of constituents of different and clearly defined wavelengths, so that it has a line spectrum in the language of ordinary optics, these different constituents will have different coefficients of absorption. In such a case, it ought to be

possible to analyse the observed curve into the superposition of a number of simple exponential curves, one for each constituent of the radiation. [中文](#)

Actually, it is found that this can be done. Different experimenters do not obtain results which are altogether accordant, but all agree in finding that there is a long stretch, near the end of the range of the radiation, over which its intensity decreases according to a simple exponential law. This can only mean that one particular constituent of the radiation is so much harder than the others that it persists in appreciable amount after traversing a thickness of matter which has completely absorbed all the softer constituents. Regener, who has studied the problem in great detail, finds that the hardest radiation of all has an absorption coefficient of 0.020 per metre of water. Other experimenters have found values which agree with this to within about 10 percent. [中文](#)

The mass of the photon can be deduced from the observed absorption coefficient μ of the radiation, by the use of a theoretical formula given by Klein and Nishina.⁶ This can be written in the form

$$\mu = \frac{2\pi N e^4}{m^2 c^4} f\left(\frac{M}{m}\right),$$

where M is the mass of the photon, m of an electron, e , c have their usual meanings, and f represents a fairly complicated function of M/m . In all the applications of the formula to cosmic radiation, M/m is quite large, and for such values of M/m , f assumes the form

$$f\left(\frac{M}{m}\right) = \frac{1}{4} \left(\frac{M}{m} + 2 \log \frac{2M}{m} \right).$$

These formulae are calculated on the supposition that the absorption is caused by N electrons per unit volume, and that these are entirely free. This last condition can never be fully realised in Nature, since every electron is bound, more or less closely, to other electric charges.

If an electron is bound to a system of mass m' , we can allow for this binding by increasing m in the formula by a fraction of m' , the fraction being large or small according as the coupling is tight or loose. Thus a loosely coupled electron behaves almost like a free electron, but an electron coupled tightly to a massive system, such, for example, as a proton or an atomic nucleus, behaves like an electron of very great mass, and the formula shows that this has no appreciable absorbing power. 中文

The Klein–Nishina formula has been tested by comparing it with observation for γ -rays. In the case of the lighter elements, it gives values which agree well with the observed absorption, provided all the extra-nuclear electrons are treated as free, while the nuclear electrons are disregarded entirely. It is natural to disregard these, because the coupling of nuclear electrons in the lighter elements is known to be so close that even the hardest γ -rays make but little impression on them. This is true for the lighter elements only; in the case of lead, Chao⁷ has found an additional scattering of the hardest γ -rays, which he believes to be of nuclear origin. In other words, he finds that some at least of the nuclear electrons in lead are not so closely coupled as to resist the onslaught of the hardest γ -radiation. Still less, then, can they be so closely coupled as to resist the incidence of the far more massive photons of cosmic radiation. From theoretical considerations of a very general nature⁸ it appears probable that in dealing with cosmic radiation, the N in the Klein–Nishina formula should refer to all electrons, nuclear as well as extra-nuclear, and not merely to the latter. A further term ought also to be added to represent scattering by nuclear protons, but calculation shows that this is entirely insignificant in amount. The result of taking the nuclear electrons into account is to replace atomic number by atomic weight, so that the absorption by a given thickness of matter becomes strictly proportional to the mass of the matter, and absolutely independent of its nature, except possibly in so far as a further small absorption,

caused by photoelectric action, may depend on the latter. The effect of this is to double, or more than double, the capacity of all atoms except hydrogen for absorbing cosmic radiation; it increases the absorbing power of water to 80 percent above the value usually calculated.

中文

The following table shows the absorption coefficients (per metre of water) which I have calculated for the radiation produced by the synthesis of iron and by the annihilation of 1 and 4 protons respectively, with their accompanying electrons. The calculation is based on the Klein–Nishina formula, all electrons, including the nuclear electrons, being treated as absolutely free:

Process	$\frac{M}{m}$	Calculated μ (per metre, water)	Observed μ (Regener)
$56\text{H} \rightarrow \text{Fe}$	876	0.136	..
$+, - \rightarrow 0$	1845	0.071	0.073
$4+, 4- \rightarrow 0$	7380	0.020	0.020

The last column gives the absorption coefficients of the two most penetrating constituents of cosmic radiation, as analysed by Regener. Their agreement with the figures in the preceding column is probably well within errors of observation and analysis, and is rather too good to be attributed with much plausibility to mere accident; the odds against a double agreement, within 5 percent in one case and 2.7 percent in another, being about 3000 to 1. This seems to me to suggest quite strongly that the most penetrating constituent so far observed in cosmic radiation may originate in the annihilation of an α -particle and its two neutralising electrons (the components of a helium atom), while the next softer constituent may originate in the annihilation of a proton and its one neutralising electron (the components of a hydrogen atom).

中文

An alternative possibility, which was first suggested by Millikan and has been championed mainly by him, is that the cosmic radiation may result from the building of electrons and protons into atoms. Yet the hardest constituents of the cosmic radiation appear to be far too hard

to be produced by the synthesis of iron, while Millikan himself considers that the synthesis of heavier elements is probably ruled out by their rarity in the universe. If, as I have suggested, the annihilation of matter is the true origin of the two hardest constituents of the cosmic radiation, then it becomes possible to suppose, with Millikan, that the softer constituents are produced by the synthesis of simple atoms into complex. Many will, however, hesitate to accept such a mixed origin for the radiation. It certainly seems simpler to suppose that the two hardest constituents, and these alone, form the fundamental radiation, while all other constituents represent mere softened or degraded forms of these. Yet this supposition brings its own difficulties, since if we measure the intensity of the radiation by its ionising power, the supposed secondary radiation is found to have many times the ionising intensity of the primary. But whatever the origin of the softer constituents may be, the two hardest constituents, with their photons equal in mass to the atoms of hydrogen and helium respectively, appear to provide weighty evidence that matter can be, and is, annihilated somewhere out in the depths of space. If we can assume that this process occurs on a sufficiently large scale, this supposition brings order and intelligibility into a vast series of problems of astronomy and cosmogony in a way in which no other suppositions can. [中文](#)

The Place of Production of the Cosmic Radiation

Various suggestions have been made as to the place of origin of this highly penetrating radiation. Many of them are put out of court by the fact, which must now, I think, be regarded as well established, that the radiation is nearly constant in intensity at all times of day and night,⁹ any variation being, at most, of the order of one part in 200. There seems to be a real variation of this amount, but in the main it appears to follow the variation of the barometer. Millikan considers that it is adequately explained by fluctuations in the absorbing power

of the air blanket formed by the earth's atmosphere. It was at one time suggested that the radiation might consist of electrons ejected from thunder-clouds high up in the earth's atmosphere, or of electrons moving with enormous speeds acquired by drifting through electrostatic fields in space, the potential gradients in these fields being slight, but the potential differences immense simply on account of the vast extent of the fields. Even if the radiation could still be treated as corpuscular, it would be very difficult to reconcile either of these suggested origins with the steadiness and uniformity with which the radiation falls on the earth's surface. [中文](#)

The fact that the intensity of the radiation is very approximately independent of both solar and sidereal time seems to show that no appreciable part of the radiation comes from the sun or stars. Counting the sun as a star, we receive more than 100,000,000 times as much starlight at midday as at midnight, yet apart from the purely local "barometer" effect just mentioned, we receive the same intensity of the radiation at both times. The fact that the intensity is approximately independent of the position of the Milky Way seems to show that the bulk at least of the radiation must come even from beyond the confines of the galactic system, thus justifying the name "cosmic radiation". [中文](#)

Where, then, does the radiation originate? For reasons which will be clear at the end of our quest, it is simpler to conduct our search in time rather than in space. The average density of matter in space is probably of the order of 10^{-30} gm. per c.c., and in each second of its existence, a beam of cosmic radiation passes through a layer of space 3×10^{10} cm. thick. Thus every second it passes on the average through 3×10^{-20} gm. per sq. cm. of its cross-section. We have, however, seen that the hardest constituent must pass through 50 gm. per sq. cm. before it is reduced in intensity by one percent, and this requires an average time of 16×10^{20} seconds, or about 5×10^{13} years—a period

which, on any reckoning, is greater than the age of the stars; its intensity is reduced to $1/e$ times its original value after 5×10^{15} years, which is greater, so far as we know, than the age of the universe.

[中文](#)

Thus, to an approximation, we may think of the hardest constituent of the cosmic radiation as indestructible, since the universe has not yet existed long enough for any appreciable amount of it to be absorbed. To a slightly less good approximation, the same is true of the softer constituents. This leads us to regard space as being permeated with all, or nearly all, of the cosmic radiation which has ever been generated since the world began. The rays come to us as messengers, not only from the farthest depths of space, but also from the remotest eras of time. And, since we cannot produce cosmic rays on earth, their message appears to be that the physics which prevails out in these far depths of space and time is something different from our terrestrial physics: different processes result in different products. So far as we can read the riddle of the rays, one at least of these processes appears to be the annihilation of matter, although whether this annihilation is taking place now, or occurred only in the remote past, or even only at the beginning of the world's history, we have no means of knowing; all that the rays show is that somewhere and sometime in the history of the universe, matter has been annihilated. [中文](#)

Similar remarks may be made with respect to the softer constituents. Millikan believes that these originate in the synthesis of complex atoms out of lighter ones, and so argues that the act of creation is still in progress. But these softer constituents also have such high penetrating powers as to be virtually indestructible. Even if Millikan's interpretation of the origin of these rays were established, it would only prove that synthesis of matter had occurred somewhere and sometime during the long past history of the universe; it would not prove that any such synthesis was still in progress. [中文](#)

Indeed, the fact that the radiation does not vary in intensity with the position of the Milky Way may be thought to suggest that it is merely a relic of past eras in the history of the universe. It may be argued that if the radiation were still being generated, the huge mass of the Milky Way, comparatively close to our doors, would surely make its influence felt. It is, however, possible (and, I think, likely) that the radiation is still being generated in extra-galactic nebulae of earlier type than the galactic system; it may be that they only emit this radiation before they condense into stars; and that the atoms which can produce such radiation in the galactic system are all shut up inside the stars, so that the radiation is transformed into starlight before it reaches us. [中文](#)

Millikan has estimated that the total amount of cosmic radiation received on earth has about a tenth of the energy of starlight, sunlight not being counted in. Near the earth, the energy of radiation from the stars is intense enough to raise space to a temperature of about 3.5 degrees absolute, whereas the energy of cosmic radiation will raise this space only to about 2 degrees absolute. Out in the inter-galactic darkness the position is reversed. Here the feeble starlight and star-heat from distant galaxies can at most raise space to a fraction of a degree above absolute zero, but the intensity of cosmic radiation is probably the same as nearer home, corresponding to about 2 degrees absolute. Space as a whole appears likely to contain far more of cosmic radiation than of light and heat, although in assessing this fact, we must remember that cosmic radiation is virtually endowed with immortality, whereas ordinary radiation, in the form of light and heat, is not. The total annihilation of all the matter in the universe would raise space to about 10 degrees absolute, so that the cosmic radiation we observe could be produced by the annihilation of quite a small fraction of the universe. [中文](#)

This is not surprising, since the cosmic radiation which pervades space

is necessarily quite distinct from the similar radiation which astronomers regard as the source of stellar light and heat. The annihilation of matter in stellar interiors would produce radiation of exactly the same high frequency as the observed cosmic radiation, but as this radiation fought its way outwards to lower temperatures, and finally to outer space, it would be continually softened, by a long succession of Compton encounters, until it finally emerged in the familiar form of starlight—ordinary temperature radiation at anything from $1,650^{\circ}$ abs. to about $60,000^{\circ}$ abs.; none of it could reach the earth in its original form. [中文](#)

The mere fact of its not having been completely absorbed shows that the cosmic radiation we receive on earth cannot have passed through more than a few kilometres of stellar matter at most; its penetrating power, high though it is, will not carry it through a greater thickness of matter than this. Consequently, it can scarcely have been generated at a place where the temperature was more than about 100,000 degrees. We must suppose that it originated fairly near to the surfaces of astronomical bodies, or, more probably still, in unattached atoms or molecules in free space. In contrast to this, the radiation which provides the energy poured out by the stars was probably generated in their central regions. Thus it must have been generated in matter at very high temperatures, while the similar radiation we receive on earth must have been generated at comparatively low temperatures.

[中文](#)

Physical Principles

According to classical theories of electro-magnetism, any acceleration of a moving electron is accompanied by an emission of radiation, of amount given by the well-known formula of Larmor. Thus an electron, describing an orbit in an atom of, say, hydrogen, must continually radiate energy away, so that the orbit will continually shrink. [中文](#)

The quantum theory replaces this continuous emission of energy by a succession of discontinuous emissions; at each moment there is a definite calculable chance that the orbit will shrink in size by a finite amount, and emit a photon in the process. The orbit of lowest energy is anomalous; when an electron is describing this orbit, no further shrinkage in orbit or emission of radiation is possible. [中文](#)

The concept of annihilation of matter removes this anomaly by providing a state of still lower energy, in which proton and electron have both disappeared in radiation. The energy emitted in the process of annihilation corresponds, of course, to that which would be emitted continuously on the classical electro-dynamics while the orbit was shrinking to zero radius. [中文](#)

Although neither the new quantum theory nor the theory of wave mechanics in any way predicts that this process must actually happen, they are in no way definitely antagonistic to its occurrence. Certain forms of both, on the whole, seem rather to favour the possibility, but theoretical calculation based on these does not at present agree with numerical estimates derived from astronomical evidence. Dirac¹⁰ has recently calculated the probability of annihilation given by the new quantum theory, and obtained a value which is substantially too large; according to his calculations, the universe ought to have dissolved into radiation long ago. Or, to put the same thing in another way, the stars ought to radiate energy far more furiously than they do. [中文](#)

The general principles of the quantum theory show that annihilation of matter might either occur spontaneously, after the manner of radioactive disintegration, or might be incited by a sufficiently high temperature, like the atomic changes which produce ordinary temperature radiation. The second process will only occur when the matter is traversed by photons with energy equal to that set free by annihilation of matter; the requisite temperature is found to be of the order of a million million degrees. Now it is quite impossible that the

cosmic radiation we receive on earth can have originated in regions where the temperature approaches this; indeed, we have seen that it can scarcely have been more than $100,000^\circ$ or so. Thus this radiation can only have originated from spontaneous annihilation. Cosmic radiation can, and very possibly does, provide evidence of the spontaneous annihilation of matter at low temperatures, but it cannot, from the nature of the case, give any evidence of annihilation being produced by high temperatures, since any radiation so produced could never get out to empty space. [中文](#)

There seem to me to be two strong reasons for supposing that this latter process is not operative in the stars, and that any radiation which is produced by annihilation inside the stars must be produced spontaneously, like the cosmic radiation which is produced outside.

[中文](#)

In the first place, if the generation is not spontaneous, the temperature at the star's centre must be of the order of a million million degrees. An immensely steep temperature gradient would be needed to connect this temperature with that of a few thousand degrees at the surface of the star, and so steep a gradient can only be reconciled with the observed flow of heat out of the star by postulating a very high opacity for the stellar material. It has so far proved impossible to reconcile such a high value for the opacity with the theoretical value given by Kramers. [中文](#)

The second reason is as follows. If the generation of energy results from high temperature, the rate of generation will involve a factor of the usual type $e^{-Mc^2/RT}$, where M is the mass annihilated. As the temperature increases from zero up, this factor first becomes appreciable when RT begins to be appreciable in comparison with Mc^2 . This happens at the temperature of about a million million degrees already mentioned. When this temperature is first approached, the exponential term is increasing very rapidly in

comparison with the temperature T . But a dynamical investigation shows that when this happens, the star must be very unstable. In brief, the emission of appreciable radiation would be accompanied by instability in the star, so that the very stable structures we describe as stars cannot radiate by means of this mechanism. The dynamical result has, it is true, been rigorously proved only for a simple, and very idealised, model of stellar structure; but general thermodynamical principles show that any structure in which a small change of physical conditions results in a very great liberation of heat, is likely to be unstable—in brief, it is in an explosive state. 中文

On the other side, there is one strong argument against supposing that stellar radiation is produced by spontaneous annihilation of matter; it is that if the sun's heat were produced by the spontaneous annihilation of its atoms, we might, expect that the earth's atoms would be subject to spontaneous annihilation at an equal or similar rate. Yet calculation shows that annihilation at even a ten-thousandth part of this rate would make the earth too hot for human habitation. Clearly, then, no appreciable annihilation of matter can occur inside the earth. This must be formed of atoms of a kind which do not undergo spontaneous annihilation, and if the sun derives its heat from the spontaneous annihilation of atoms, these must be of a different kind from the atoms of which our earth is formed. This is not in itself unreasonable; from the mode of the earth's formation, its atoms can be a sample only of those in the sun's outer layers. If we conjecture that those kinds of atoms which undergo spontaneous annihilation are of very great atomic weight, and so sink to the interiors of the stars, this difficulty disappears, and with it the problem of why no cosmic radiation is received directly from the Milky Way. 中文

(128, 103-110; 1931)

1. *Proceedings: National Academy of Sciences* (Oct. 1930).
2. *Nature*, **127**, 924 (June 20, 1931).
3. Millikan, Dec. 29, 1930, Lecture at Pasadena, reprinted in *Nature*, **127**, 167 (Jan. 31, 1931).
4. *Physical Review* (April 15, 1931).
5. *Proc. Roy. Soc.*, **122**, 647.
6. *Nature*, **122**, 398 (Sept. 15, 1928).
7. *Physical Review* (Nov. 15, 1930).
8. *Nature*, **127**, 594 (April 18, 1931).
9. Hess, V. F., *Nature*, **127**, 10 (Jan. 3, 1931).
10. *Proceedings of Cambridge Philosophical Society* (July 1930).

* The substance of lectures delivered before the Universities of Princeton, Yale, and Harvard on May 23, 26, and 27 respectively, under the auspices of the Franklin Institute of Pennsylvania.

物质的湮灭*

詹姆斯·金斯

詹姆斯·金斯在文中指出：科学发展最神圣的原则之一是新旧理论的更迭。几百年来，物理学家们一直对物质既不能产生也不能灭亡这一原则深信不疑。可是现在，他指出，人们越来越相信恒星只有通过物质的湮灭过程才能获取能量。有证据表明：一般的恒星早已在过去的岁月里辐射掉了现有质量的好多倍。恒星存在的过程似乎就是其物质不断湮灭的过程，因为有质量的粒子会将其能量用于产生辐射。现在人们利用核聚变原理来解释这一现象，质量和能量的相互转化关系可以由爱因斯坦方程 $E = mc^2$ 表示。 [英文](#)

在贯穿整个科学史的大部分时间里，物质都被看作是守恒的，它们既不会凭空产生，也不会凭空消失。但是现在大量天文学的证据似乎表明，物质的湮灭是恒星辐射能量的唯一来源。从而出现了这样一种局面：大多数天文学家认为物质湮灭可能是宇宙中的一个基本过程，而同时，许多也可能是大部分的物理学家对这种可能性持谨慎态度，甚至干脆不相信。我一直认为试着评述与这个问题相关的现状会是一件有意义的事情。 [英文](#)

天文学的证据

天文学上关于物质湮灭的论证，不是以恒星辐射的强度为依据，而是基于恒星存在的时间。尚未发现一种不如完全湮灭那么剧烈的能量转化，能够在恒星显然存在的漫长岁月里，始终为其提供持续辐射所需要的能量。所有可以用来估算恒星寿命的方法都表明，整体看来，恒星已经存在了万亿年，只有一个方法明显例外，我将在后面讨论它。 [英文](#)

文

有些方法取决于临近恒星的引力作用速度；例如，恒星穿越空间的速度表明它的能量是近似均分的，而要实现这样的均分必须经过数以万亿年的时间。被称为运动星团的星群中的个体成员，由于在其旁边经过的恒星的一定程度上的引力作用，它们的路径已经出现了改变，这再次表明活动过程已延续了数万亿年。目视双星的轨道也是如此。在这三个例子中，我们所使用的时钟的单位时间类似于在气体理论中所称的“弛豫时间”；在这个类比中，单个恒星被当作单原子分子处理，双星被当作双原子分子，而运动星团的瓦解对应于气体的扩散过程。

英文

当然，只有当我们假定其他恒星的引力作用是引起恒星运动和排列改变的唯一原因时，这些对恒星年龄的估计才成立。可以想象其他原因也是存在的，并且必然在某些方面有一定的贡献——辐射压力，由宇宙空间中的游离物质或弥散在空间中的宇宙云原子造成的轰击。但是计算表明源于这些过程的贡献是相当微不足道的。实际上，当我们把这些因素考虑进去时，对恒星运动的讨论就不再是一个天文学问题，而变为一个物理问题；我们必须把恒星当作是在物理介质中作布朗运动的“粒子”。做这样的处理之后，我们发现这个布满恒星的介质，以我们谈及运动着的布朗粒子的温度的方式而论，它的温度可达 10^6 度数量级。单个恒星和双星都表现出与此数量级温度相对应的能量均分，显而易见，物理中介作用，比如辐射压力和原子压力等建立平衡的温度要低得多，只有 10^4 度的量级，不可能对建立均分的过程有任何可观的贡献；它们不过是作为恒星运动的阻力罢了，平均而言往往是在减慢它们的速度。

英文

在第二类双星系统，即光谱双星中，两颗子星是如此之近，以至于从它们附近经过的恒星对它们两个的吸引效果几乎相同，因此就不能以不同的作用效果改变双星系统组成物的相对轨道。显然对于这种系统的内部运动，毫无疑问可以采取任意近似方式以达到其能量均分的状态。尽管如此，仍然可以描绘出双星系统结构所固有的演变过程，从仍相互接触的两组分所处的近似圆轨道开始，这很可能就是一个系统刚刚分裂形成的状态；然后继续发展到形状远不是圆的轨道，此时这两个组分产生了实质上的分离。尽管还不能确定，但似乎可以认为这种演变过程就是一种老化的过程。当母星刚刚分裂形成双星系统时，新形成的系统从

刚提到的结构变化的末端，逐渐沿着一系列变化过程演化。现在观测表明，毫无疑问，处于该演化过程末端的恒星所具有的质量大大低于初始阶段的质量。我们知道不同类型恒星以辐射形式损失质量的速率，由此可以计算出为产生存在于演化过程两端的质量差而需要的时间。结果再一次证明这个过程需要数万亿年。在这里我们所用的度量标准是恒星辐射的流失率，或与之相对应的，物质损失率。 [英文](#)

反对这几种估算方法的人一定会提到这样一个证据，如果用最一目了然的方式解释的话，它似乎会得出完全相反的结论。即遥远的河外星云的谱线都发生了红移，红移量与星云的距离近似成正比，但不精确。如果这个现象被解释成最直接的原因，即多普勒效应，则这些星云必须全部从我们身边分散开去，并且在空间中互相远离。远离的速度是如此之大以至于大约每过14亿年宇宙的尺度就要增加一倍。这样的膨胀率似乎完全无法与之前对恒星存在了万亿年的估计相符。计算表明宇宙的初始半径必须在12亿光年量级（爱丁顿），而现在的宇宙半径似乎只有20亿光年量级（德西特）。如果可以把以上的这些估计看作是准确的，那么我们就可以确定宇宙的年龄只比10亿年多一些，甚至比由地球上岩石的放射性推得的地球年龄小很多。没有人对这两种估计的精确性提出太高的要求，尤其是对第二种，但总的情况似乎不允许宇宙在这万亿年间每14亿年就膨胀一倍。 [英文](#)

尽管还有其他站得住脚的解释可供选择，但它们中没有一个可以让人完全信服，因而目前的局面令人十分困惑。尽管现在还有很多意见分歧，许多天文学家认为，其他一些关于星云存在明显退行的解释将很可能被适时发现。到那时，由大量天文学证据所支持的恒星已存在万亿年的观点就可以毫无阻碍地得到人们的认可了。 [英文](#)

如果暂时接受这样的恒星年龄，那么通过计算可以得到，普通恒星已经辐射出相当于自身质量很多倍的能量了。换言之，普通恒星在诞生之初的质量必定是现在的很多倍。确实，光谱双星的演化过程为我们描画了一颗典型恒星的生命历程。它最初的质量是太阳质量的10到100倍，而终结时，它的质量与太阳的质量不相上下，甚至比太阳的质量还要小。很难想象，若不是以实物原子或者至少以实物电子和质子的形式，这些新生恒星的巨大能量能存储在哪里。因此我们就得到了这样的

结论，恒星的生命历程就是其自身物质不断湮灭的过程，电子和质子相互湮灭，并以这种方式为恒星辐射提供能量。至少，从天文学上我们可以得到这样的推测，而检验这些推测则要有赖于物理学了。 [英文](#)

高穿透性辐射

如果要找出湮灭过程的直接证据，那么该证据最有可能从本世纪初麦克伦南、卢瑟福和其他科学家在地球大气中发现的穿透力很强的辐射中获得。这是因为在整个物理学中只有这里涉及的辐射光子的质量与期望中由电子和质子湮灭产生的光子质量相当，这些我们在后面还会谈到。最近几年，赫斯、密立根和雷格纳等人十分细致地研究了这种辐射。他们的研究几乎不容置疑地表明这些辐射是从外太空进入到地球大气的；这就是这些辐射通常被称为“宇宙射线”的原因。 [英文](#)

一开始人们理所当然地认为这种辐射本质上肯定是 γ 辐射，因为它的穿透力比被认为有可能的任何种类的粒子辐射都强。现在看来这个理由并不充分，理论研究已经证明粒子辐射，包括 α 粒子和 β 粒子的辐射，可能拥有和观测到的辐射一样强的穿透力。 [英文](#)

然而其他的论证已经十分令人信服地表明这种辐射不可能是 α 或 β 辐射。简言之，其中心论点是，由带电粒子构成的辐射会受到磁场的影响，而宇宙辐射则不会。运动着的电子或其他带电粒子会受到磁场的作用，这是由于它在运动；它运动得越快，磁场对它施加的力也就越大。这种辐射的穿透力非常强，只有以很高速度运动的带电粒子才能达到这么强的穿透力。如果一大群这样的粒子进入地球磁场，高速运动会使它们绕着非常接近地球磁力线的轨道做螺旋运动，结果在地球磁极附近落下的粒子要远远多于其他地方的粒子。爱泼斯坦^[1]估计对于一大批电子，若要具有宇宙辐射那样的穿透力，它们必须以大约穿过10亿伏特才能获得的能量运动，他还计算出以这个能量运动的入射电子将被完全限制在两磁极附近的相对较小的圆里。而实际上，观测到的辐射非常平均地落在地球表面的各个区域，并没有发现明显的差异。英国、澳大利亚、新西兰共同组成的南极探险队^[2]的成员发现，在南磁极周围250英里区域内的辐射强度，与他们之前在南澳大利亚测得的，以及其他人在美国、加拿大和北大西洋得到的结果相同。此辐射具有极硬 γ 辐射的性

质这一点似乎是无可置疑的^[3]。 [英文](#)

最初，博特和科尔霍斯特的一些实验结果似乎不支持这个推论。他们设置了两个盖革计数器，将其中一个垂直置于另一个的上面，并且发现如果这个辐射是粒子辐射，两个计数器记录的同时放电的粒子数几乎与用纯几何方式预计的结果相同。当然，产生这些电离的辐射不一定是从外太空进入地球的初级辐射。当任何初级辐射穿过大气层时，都必然会产生各种类型的次级辐射，其中任一种次级辐射都可能会直接导致博特和科尔霍斯特在实验中观察到的电离作用。首先进入地球大气的初级辐射非常可能是电磁辐射，而造成电离的辐射则是次级粒子辐射。

[英文](#)

为了检验这种可能性，博特和科尔霍斯特在两个计数器之间放置了一块金板。这自然就会造成同时发生放电的粒子数目减少，并且通过减少的数量就可以计算出真正引起电离的辐射的穿透力。结果发现它的穿透力和初级辐射的穿透力近似相同。假若是初级辐射本身造成了计数器中的电离作用，并且它本质上是粒子辐射，那么到目前为止的所有现象都可以得到解释。 [英文](#)

最近莫斯-史密斯^[4]对这个解释进行了验证并发现了不足之处。他改进了博特和科尔霍斯特使用的设备，在原有的两个计数器下面加入了垂直于它们的第三个计数器。他首先证实在三个计数器中同时发生的电离个数正是我们通过它们的几何排列得到的预期值。现在，如果引发这些电离的是粒子辐射，那么它应该在磁场中发生偏转。例如，如果一个足够强的磁场加到第二和第三个计数器之间，第三个计数器应该被完全屏蔽而免受从前两个计数器穿过的辐射，因此前两个计数器的计数将保持不变而第三个将减少为零。但是莫斯-史密斯发现这种情况并没有发生。尽管他的磁场强度已经是完全屏蔽第三个计数器所需强度的很多倍，但这个磁场的加入并没有对同时电离的计数情况产生任何影响。这表明电离辐射不是粒子性的，而博特和科尔霍斯特也已经指出电离辐射很可能就是初级辐射，这样就证实了密立根和爱泼斯坦的理论依据，从而得到初级辐射具有 γ 辐射的性质。 [英文](#)

产生辐射的模式

如果就像前面的讨论和实验所表明的那样，初级辐射具有 γ 辐射的性质，那么它的起源就应该能够通过其穿透力揭示出来。这样的辐射由光子构成，可以把它们比作许多发以相同速度——光速运动着的子弹。因而它们的穿透能力也仅由其质量决定，并且我们可以通过理论研究从一个光子推导出另一个光子。然而每个光子都起源于原子激变，并且光子的质量精确地等于母原子在这个激变过程中减少的质量。例如，如果这里的原子是氢原子且激变由湮灭过程组成，那么湮灭产生的光子的质量必须精确等于氢原子的原始质量，即 1.66×10^{-24} g。再比如，无论什么原子中的一个质子和一个电子相互之间发生了湮灭，这在整体上减少了原子量，那么产生的光子的质量必定等于原子中原来位置上的电子和质子质量之和。除去少量的“结合部分”的质量外，它也与氢原子的质量相等。

[英文](#)

研究宇宙辐射穿透力最有效的方式，是把合适的仪器沉入到湖面以下不同深度，并观测入射的宇宙射线在不同深度被水吸收后引起的电离作用。密立根、雷格纳和其他一些人非常细心巧妙地完成了这样的实验观测。

[英文](#)

他们的结果很难解释。格雷指出^[5]有一种软化效应持续在起作用。由于这种效应持续在起作用，当一个能量量子被吸收时，就会产生一个反冲电子，这个电子反过来又引起了能量辐射。辐射的能量与原始量子的能量相比，尽管略低一些，但也大致相当。当辐射在吸收介质中传播一段距离之后，观察到的电离就不再能反映未被吸收的初级辐射的真实强度，而是对应于与所有较软的次级辐射部分保持平衡的初级辐射的值。

[英文](#)

考虑到这个复杂的情况以后，就可以从电离曲线中得到穿过不同厚度吸收介质之后依然存在的真实的初级辐射强度。如果初级辐射包含波长不同的成分，那么它就会有像普通光学那样的线状谱，这些不同成分的吸收系数是不同的。在这种情况下，应该可以把观测到的曲线看作是多条简单指数曲线的叠加，每一个辐射成分都对应着一条指数曲线。

[英文](#)

实际上人们发现这是可以做到的。不同的实验者并没有得到完全一

致的结果，但是他们都一致认为在辐射区域的末端附近有一段很长的延伸范围，在这个范围内辐射强度呈简单的指数率衰减。这只能说明辐射中存在着一个特殊的成分，它比其他成分硬很多，以至于在经过一定厚度的介质后，所有较软的成分都已经被完全吸收，而这个成分的辐射仍然保持着相当的强度。雷格纳在对上述现象进行了仔细的研究之后发现，全部辐射中最硬的那个成分在被水吸收时的吸收系数为每米0.020。其他实验者得到的数值与此一致，偏差不超过10%。 [英文](#)

利用克莱因-仁科给出的理论公式，我们可以从观测到的辐射吸收系数 μ 中推导出光子的质量^[6]。这个公式可以由下面的形式给出：

$$\mu = \frac{2\pi Ne^4}{m^2 c^4} f\left(\frac{M}{m}\right),$$

其中： M 为光子质量， m 为电子质量， e 、 c 为它们的通常定义， f 表示以 M/m 为变量的一个相当复杂的函数。对于所有的宇宙辐射，该公式中的 M/m 都非常大，而当 M/m 取这些值时，可以假设 f 有如下形式：

$$f\left(\frac{M}{m}\right) = \frac{1}{4} \left(\frac{M}{m} + 2 \log \frac{2M}{m} \right)。$$

这些公式的计算基于这样的假设：吸收是由单位体积内 N 个完全自由的电子所引起的。电子是完全自由的这个条件在自然界中永远不可能完全满足，因为每个电子都会被其他电荷束缚着，不论束缚是强是弱。如果一个电子被一个质量为 m 的系统所束缚，那么对于这种情况我们可以考虑把 m 的一部分增加到公式中的质量 m 上，增加部分的大小取决于耦合的强弱。因此弱耦合电子的表现几乎与自由电子一样，但是对于一个与质子或原子核等大质量系统紧紧耦合的电子，它会表现得如同质量非常大的电子，公式表明在这种情况下它不具有明显的吸收能力。 [英文](#)

通过与观测到的 γ 射线进行比较，人们已经检验了克莱因 - 仁科公式。对于较轻的元素，它给出的值与观测到的吸收曲线符合得相当好，条件是这里所有的核外电子都被当作自由电子处理，同时完全忽略核内电子。这样的忽略是自然的，因为我们知道较轻元素的核内电子耦合很强，即使是最硬的 γ 射线也只会对它们造成很小的影响。但是，这仅对较轻元素成立；就铅而言，赵^[7]发现在最硬的 γ 射线下存在一个附加散

射，他认为这来源于原子核。换句话说，他发现至少铅的某些核内电子的耦合强度还抵御不了最硬 γ 辐射的冲击。更不用说以它们的耦合强度去抵御数量巨大的宇宙辐射光子的冲击。从理论角度作非常一般性的考虑^[8]，在处理宇宙辐射时，很可能克莱因 - 仁科公式中的 N 指的是包括核内和核外的所有电子，而不应该仅仅是后者。此外还应该增加一项，用来表示原子核内质子的散射，然而计算表明质子散射的作用量很小，完全可以忽略不计。把核内电子计算在内的结果就是要用原子量取代原子序数，因此对于给定厚度的介质，它的吸收就严格正比于射线所经过区域的介质质量，而与它的性质毫无关系，除非是由光电效应造成的更少量的吸收有可能与后者相关。这样就使除氢以外的所有原子在吸收宇宙辐射的能力上加倍，甚至大于原来的两倍。经过这样的处理，水的吸收能力比通常的计算值高出了80%。

英文

对于由铁的合成以及由1个质子和4个质子分别与它们的伴随电子发生湮灭而产生的辐射，我分别进行了计算，并在下表中给出了吸收系数（水中，每米）。结果是根据克莱因 - 仁科公式计算出来的，计算过程中把所有的电子，包括核内电子，都视为自由电子：

过程	$\frac{M}{m}$	计算值 μ (水中，每米)	观测值 μ (雷格纳)
$56\text{H} \rightarrow \text{Fe}$	876	0.136	..
$+\gamma \rightarrow 0$	1845	0.071	0.073
$4+4 \rightarrow 0$	7380	0.020	0.020

最后一列给出的是宇宙辐射中两种穿透力最强的成分的吸收系数，这是雷格纳通过分析得到的。观测值与前一列中的计算值也许相符得还不错，其偏差在观测和分析所引起的误差范围内。很难把这么好的符合度仅仅归因于巧合。两次吻合，一次误差在5%以内，另一次在2.7%以内，出现错误的概率为1/3,000。在我看来这个结果强烈地显示出：在迄今为止观测到的宇宙辐射中，穿透力最强的成分有可能起源于一个 α 粒子和它的两个使其变为电中性的电子（组成氢原子的成分）的湮灭，而另一个较软的成分可能来源于一个质子和一个使其变为电中性的电子（组成氢原子的成分）的湮灭。

英文

由密立根首先提出并且主要由他倡导的另一种可能性是，宇宙辐射起源于电子和质子形成原子的过程。然而宇宙辐射中最硬的成分似乎比铁合成过程中产生的辐射硬很多，而密立根自己也认为更重元素的合成

可以被排除掉，因为它们在宇宙中是很稀少的。如果按照我提出的，物质的湮灭是宇宙辐射中最硬的两个成分的真正来源，那么我和密立根设想，很可能较软的成分是在简单原子组成复合原子的过程中产生的。但是很多人会对宇宙辐射有多种起源表示怀疑。显然比较简单的假设是认为只有两种最硬的成分构成了基本辐射，而所有其他成分仅仅是这部分辐射的软化或降阶形式。但是这种假设给自己带来了一些难题，因为如果我们用电离能力去衡量宇宙辐射的强度，那么这个假设的次级辐射的电离强度会是初级辐射的很多倍。但是无论较软成分的来源是什么，这两个最硬成分中的光子所具有的质量分别与氢原子和氦原子的质量相同，这似乎为物质可以在遥远的空间中湮灭提供了有力的证据。如果我们假定这个过程发生在一个足够大的尺度内，那么这个假设就会使大量的天文学和宇宙学问题变得有条理并且易于理解，这是其他假设无法做到的。

[英文](#)

宇宙辐射产生的位置

对于这种高穿透性辐射起源于何处人们有不同的看法。其中的很多观点都被以下这个在我看来现在已被牢固确立的事实排除掉了，即无论是白天还是黑夜，宇宙辐射的强度在任何时候几乎都是一个常数^[9]，它的变化幅度至多为1/200量级。这个量似乎确实会发生一定的变化，但主要是随着气压而变化。密立根认为这些变化用地球大气层吸收能力的涨落就足以解释。曾经有人认为这些辐射可能包含那些由地球大气中的高空雷雨云发射出来的电子，或者包含因在空间静电场中漂移而获得极高速度的运动电子。这个静电场的电势梯度虽然微不足道，但是由于电场范围极为宽广，因而电势差非常大。即便仍然认为宇宙辐射由粒子辐射产生，也很难将这些假定起源中的任何一个与落向地球表面的辐射所具有的稳定性和均匀性统一起来。

[英文](#)

辐射强度与太阳时和恒星时近似无关这一事实似乎表明，可测到的辐射不会来源于太阳或者恒星。如果将太阳当作普通恒星处理，那么我们在正午接收到的星光是在午夜接收到的星光强度的100,000,000倍。然而排除刚才提到的纯粹由局部“气压”不同引起的作用之后，我们在这两个时刻得到的辐射强度仍然相同。而辐射强度与银河系的位置几乎无关这一事实也说明，宇宙辐射中至少有一大部分会来自于银河系范围以

外，这也印证了“宇宙辐射”这个名字是恰如其分的。

[英文](#)

那么这些辐射是从哪里来的？为了能够最终找到原因，从时间入手比从空间入手更简单。宇宙中的平均物质密度约为 10^{-30} g/cm^3 ，并且在宇宙存在的每一秒钟，一束宇宙射线会穿越 $3 \times 10^{10} \text{ cm}$ 厚的宇宙空间层。因此每秒钟它穿越的辐射截面是 $3 \times 10^{-20} \text{ g/cm}^2$ 。然而我们已经发现，这个最硬成分的强度要减少1%，就必须穿过 50 g/cm^2 ，这个过程所需的平均时间为 16×10^{20} 秒，或者约 5×10^{13} 年——以任何方式计算，这个时间都要比恒星的寿命长；辐射强度减小到初始值的 $1/e$ 需要 5×10^{15} 年，比我们现在认为的宇宙的年龄都要长。

[英文](#)

因此，我们可以近似认为宇宙辐射中最硬的成分是不会衰减的，因为宇宙存在的时间长度还不足以使它被吸收的部分达到任何可观的量。也可作一个稍差一点的近似，认为较软的成分也是不会被吸收的。这使我们可以把宇宙空间看成是充满了自宇宙诞生以来到现在曾经产生的所有或几乎所有的宇宙辐射。我们接收到的这些射线不仅带来了太空最深处的信息，还带来了时间最久远的年代的信息。并且，因为我们不能在地球上制造出宇宙射线，所以它们所携带的信息显示出这些普遍适用于遥远空间和时间的物理定律有别于我们地球上的物理定律：不同的过程导致不同的结果。就我们现在对宇宙射线之谜的解读情况来看，其中至少有一个过程应该是物质的湮灭，尽管我们没有办法知道这种湮灭是发生在现在，还是发生在遥远的过去，或者甚至仅是在宇宙诞生之初；这些射线的存在已经能够充分说明，在宇宙演化史中的某个地点和某个时刻，物质发生了湮灭。

[英文](#)

类似的说明也适用于较软的成分。密立根确信它们产生于较轻原子合成复杂原子的过程之中，并因此认为这种合成还在进行。但是由于这些较软的成分同样具有很强的穿透力，因此实际上也是不会衰减的。即便密立根对这些射线起源的解释可以成立，也只能证明在宇宙漫长的发展史中，物质的合成过程曾经在某个地点和某个时刻发生过，而不能证明这样的合成仍在进行。

[英文](#)

实际上，辐射强度与银河系的位置无关这一事实也许可以这样来理解：宇宙辐射仅仅是宇宙发展史中的一个遗迹。如果这个辐射过程还在

继续，而银河系的主体又离我们那么近，显然我们应该察觉到它所造成的影响。然而还有可能（我认为非常可能）这个辐射仍然在不断地从比银河系存在时间更长的河外星云中产生出来，也许它们只在凝聚成恒星之前发出这样的辐射，而银河系中能产生这种辐射的原子都被密闭在了恒星的内部，所以辐射在到达我们这里之前已经被转变为星光了。

[英文](#)

密立根曾经估算过，在不把太阳光计算在内的情况下，地球上接收到的宇宙辐射的总能量大约为星光能量的1/10。在地球附近，恒星发出的辐射能量足以使空间的绝对温度上升大约3.5度，而宇宙辐射的能量则只能使此空间的绝对温度升高2度。在星系间的黑暗区域，情况则截然相反。在那里，来自于遥远星系的微弱星光和恒星热量最多只能使空间温度稍稍升高到绝对零度以上不到1度，而宇宙辐射的强度则可能和地球附近的强度相同，对应的绝对温度大约为2度。总体来说，宇宙空间包含的宇宙辐射很可能会远远多于光和热，虽然在确定这一点的时候我们也必须记得，事实上宇宙辐射是永远不会消失的，而以光和热为呈现方式的普通辐射则会。宇宙中所有物质的完全湮灭将使空间的绝对温度上升10度左右，因此，产生我们观测到的宇宙辐射只需要湮灭掉极小部分的宇宙物质。

[英文](#)

遍及空间的宇宙辐射和那些被天文学家们认作是恒星光和热来源的相似的辐射必然是明显不同的，这并不奇怪。恒星内部物质的湮灭会产生频率和观测到的宇宙辐射完全相同的高频辐射，但是当这种辐射向恒星外部温度较低的地方传播并最终到达外层空间时，它会因长期发生连续的康普顿散射而被不断软化，直到最终显现为我们所熟悉的星光形式——从绝对温度1,650度到绝对温度约60,000度之间的普通温度辐射，这种辐射不可能以原始形式到达地球。

[英文](#)

宇宙辐射没有被完全吸收的事实足以说明：我们在地球上接收到的宇宙辐射，不可能曾穿透过超过几公里的恒星物质；尽管它的穿透能力很强，但也不能穿过比这更厚的物质。因此，在温度高于100,000度的地方几乎不可能产生这种辐射。我们必须假设它产生于非常接近天体的表面的地方，或者，更有可能的是，产生于自由空间中的独立原子或分子。与此相反，能使恒星发出能量的辐射则可能来源于恒星的中心区

域。因此它必定是在温度非常高的物质中产生的，而我们在地球上接收到的相似的辐射应该产生于相对较低的温度。 [英文](#)

物理原理

根据经典电磁理论，任何作加速运动的电子都会产生辐射，其辐射量可由著名的拉莫尔公式给定。因此，某一个原子，比如说氢原子，其中沿一定轨道运动的电子必须持续地辐射出能量，因而其运动轨道将不断收缩。 [英文](#)

量子理论用一系列不连续的辐射取代了这种连续的能量辐射，在每一个时刻都可以确切地计算出轨道收缩一个固定值并放出光子的概率。能量最低的轨道是反常的，当一个电子处于这个轨道时，它既不可能再降低轨道，也不可能再发出辐射。 [英文](#)

物质湮灭的概念提出了一个能量更低的状态，消除了这个反常情况。在这种状态下，质子和电子同时消失并转化为辐射。当然，湮灭过程中放射的能量，应该与经典电动力学中轨道半径收缩为零时持续放射的能量相当。 [英文](#)

尽管新的量子理论和波动力学理论都没有以任何方式预言这个过程真的一定会发生，但是它们也没有以任何确定的方式来否定它的出现。两种理论的特定形式总体看来都颇为支持这种可能性，但是基于这两种理论的计算结果目前尚不能与通过天文学观测证据估算的数值相符。最近，狄拉克^[10]根据新的量子理论计算了湮灭概率，但是得到的数值明显太大了。根据他的计算结果，宇宙早就应该变为辐射消失了。或者换个说法，恒星放出能量的方式应该比现在猛烈得多。 [英文](#)

量子理论的普遍原理指出，物质的湮灭既可能是在放射性衰变之后自发发生的，也可能是被足够高的温度所激发，就像发出普通辐射的原子变化一样。第二种情况只能在当穿过物质的光子所具有的能量与物质湮灭释放的能量相等时才会发生，其需要的温度要达到万亿度的量级。而目前我们在地球上观测到的宇宙辐射根本不可能是从温度能达到这么高的区域中产生的。实际上我们发现它的温度很难超过100,000度左右。因此这个辐射只能来源于自发的湮灭。宇宙辐射能够，并且很可能

已经，为物质在低温下的自发湮灭提供了证据，但是从这种情况的本质上说，它不能提供任何高温导致湮灭的证据，因为没有任何这样产生的辐射能逃逸到太空中。 [英文](#)

在我看来，似乎有两个强有力的理由可以让我们认为后一种过程不会在恒星中发生，并且任何由恒星内部的湮灭过程所产生的辐射必定是自发发生的，就像恒星球产生的宇宙辐射一样。 [英文](#)

首先，如果恒星中的湮灭不是自发的，那么恒星中心的温度就必须达到万亿度的量级。这就需要有一个变化极大的温度梯度，以便将这个温度与恒星表面几千度的温度联系起来，只有在恒星物质不透明度非常高的条件下，这么大的梯度才可能与观测到的恒星球外热流相一致。现在已经证明如此高的不透明度不可能与克拉默斯给出的理论计算值相符。

[英文](#)

下面给出第二条理由。如果能量的产生是由高温引起的，那么产率就会引入一个通常形式为 $e^{-Mc^2/RT}$ 的因子，其中 M 是湮灭的质量。随着温度由零度开始不断升高，当 RT 升至和 Mc^2 接近的量值时，这个因子的影响开始变得明显。当温度大约达到前面已经提到的万亿度时，这种情况就会发生。第一次达到这个温度时，这个指数项与温度 T 相比，增长得非常迅速。但动力学研究表明，当这种情况发生时恒星肯定是极不稳定的。简言之，明显的能量释放总会与恒星的不稳定性相伴，因此被我们认定为结构非常稳定的恒星是不会以这种机制发生辐射的。确实，只有一个理想化程度非常高的简单恒星结构模型下，动力学结果才能得到严格的证明；但是普遍的热力学原理表明，若在一种结构中，物理状态很小的一个改变就会释放大量的热，那么任何这样的结构都很可能是不稳定的——简言之，它处在一个一触即发的状态。 [英文](#)

另一方面，对于恒星辐射是由物质自发湮灭产生的猜想，存在一个有力论据可以反驳它，即如果是在太阳自身原子的自发湮灭中产生了太阳的热量，那么我们是否可以认为地球上的原子也会以相同或者相近的速率自发湮灭。然而计算表明，哪怕湮灭速率仅是这个速率的万分之一，也会使地球非常热，以至于人类无法居住。那么显然，地球内部不可能有明显的物质湮灭。地球必须由不会发生自发湮灭的原子所构成，

而如果太阳的热量来自于原子的自发湮灭，那么这些原子与构成我们地球的原子一定不属于同样的类型。这并不是没有理由的，从地球的形成模式可知，地球上的原子可能只与太阳外层的物质相同。如果我们推测，这种发生自发湮灭的原子具有很大的原子量，因而会陷入到恒星的内部，那么不但以上的问题不存在了，而且还能解释为什么没有接收到直接从银河系发出的宇宙辐射。

[英文](#)

（周杰 翻译；尚仁成 审稿）

* 这个由美国宾夕法尼亚州富兰克林科学馆赞助的演讲分别于5月23日、26日和27日发表于普林斯顿大学、耶鲁大学和哈佛大学。

Quantum-mechanical Models of a Nucleus

R. H. Fowler

By the 1930s, physicists believed they had a fair understanding of the structure of the atomic nucleus. Its mass was considered to be due to the number of protons it contained, while some of their charge was thought to be offset by the presence of negatively charged electrons involved in β -decay. But even so, it was not clear how so many protons, repelling one another, could be stably packed into so small a space. Here physicist Ralph Fowler suggests an explanation for the stability of nuclei which relies on the observation that radioactive atoms may emit α -particles. The real explanation invokes another nuclear particle, the neutron, not discovered until 1932. [中文](#)

IN their recent paper,¹ Lord Rutherford and Dr. Ellis have shown how the numerous γ -rays of radium C' can be arranged in a simple and orderly manner, which suggests, as they point out, that the multiplicity of the γ -rays is largely due to the excitation of several α -particles into the same excited level rather than to the excitation of one α -particle into several excited levels. Their arrangement of the lines of radium C' is probably not a unique scheme of this sort, but any reasonable scheme appears likely (they show) to present the same general features. [中文](#)

It seems desirable therefore to investigate theoretically in detail any simple model or models of a nucleus consisting of some fifty α -particles, which might show such general features. The main feature brought out by Rutherford and Ellis is that the γ -rays can be expressed in the form

$$h\nu = pE_0 - qE_1,$$

where p is an integer running from 1 to 4 and q an integer running from 0 up to perhaps 10; the value of E_1 is about $\frac{1}{16}E_0$ for radium C' and has much the same value for radium B. For radium C' more than one value of E_0 may be required. [中文](#)

There are two models which might be investigated with some chance of success; the first is a model in which each α -particle is considered to move independently in a central field (which is ultimately to be referred to the combined interactions with the other α -particles), but the whole family is affected by perturbing interactions of the form $V(r_{ij})$, between each pair i, j of all the α -particles, where r_{ij} is the distance between the α -particles i and j . Such a model is very like an atom of electrons, except that wave functions have to be symmetrical in the α -particles instead of antisymmetrical in the electrons, and this is the essential difference which allows of the states of reduplicated excitation, which do not occur at all in atoms. This model can be still further simplified from a three-dimensional to a one-dimensional form for a first discussion. [中文](#)

The second model is one in which each pair i, j of α -particles act on one another with a potential energy $\frac{1}{2}\lambda r_{ij}^2$. This model is obviously a rather poor physical approximation to the type of force, but it has the advantage that it can be studied exactly and not merely by the approximations of a perturbation method. A discussion of both these models has been begun, but has as yet only been carried through for the first model simplified to one dimension. [中文](#)

Confining attention only to the most general features, likely to be true of any suitable similar model, the following results have been obtained, which are to a large extent in excellent accord with the scheme of Rutherford and Ellis, but also seem to indicate clearly that a rather more elaborate scheme should be adopted. The energy levels of the model which arise from excitation of more than one α -particle into a single excited state are of such a configuration that the corresponding γ -rays (if they could all be emitted) would be approximately of the frequencies

$$h\nu = p(E_0 - qE_1)$$

These frequencies agree with those of the proposed scheme of Rutherford and Ellis if the scheme is only very slightly modified, so that in place of the proposed single set of γ -rays of frequencies $2E_0 - qE_1$, we have the double set of frequencies $2(E_0 - qE_1)$ and $2(E'_0 - qE_1)$ with E_0 and E'_0 nearly equal, and in place of the single set $3E_0 - qE_1$, the triple set $3(E_0 - qE_1)$, $3(E'_0 - qE_1)$, $3(E''_0 - qE_1)$ and so on. It is, moreover, clear that the reduplication of the upper levels is to be expected when we consider the three-dimensional version of the model. Further, the theory suggests that the ratio E_0/E_1 should be numerically somewhat less than $\frac{1}{2}n (= 26)$ in not too bad conformity with the observed value 16 for radium C'. The theory even suggests further that both E_0 and E_1 , or perhaps rather E_1 , will not vary very much between one radioactive nucleus and another. It is true that the observed values of E_1 (but not those of E_0) are much the same for radium C' and radium B. The γ -rays of other atoms have not yet been analysed in this way. 中文

All these features are general and the conformity very reassuring. One can, however, further estimate the relative frequency of the emission of the various γ -rays corresponding to the transitions from a state of q -excited α -particles to states of $q-1$, $q-2$, $q-3$... excited α -particles. With an interaction energy of the proposed form, the transitions $q \rightarrow q-3$

should be absent, or at most very rare, and the transitions $q \rightarrow q-4$, $q \rightarrow q-5$, etc., entirely absent. The theory gives as a first approximation to R , the ratio of the frequency of occurrence of the transitions $q \rightarrow q-2$ and $q \rightarrow q-1$, the value

$$R\left(\frac{q \rightarrow q-2}{q \rightarrow q-1}\right) = \frac{q-1}{6.5} f$$

where f is a factor certainly less than unity and probably not so small as $1/10$. The absolute value of the ratio R may be heavily affected by higher order terms, and we need not be concerned if the proposed scheme does not conform closely. The feature of R that is almost certainly of general importance is that R increases with q . This feature ought to be carefully borne in mind in the construction of any amended scheme. It is not yet possible to say whether these features can be incorporated in an otherwise satisfactory scheme, and a detailed re-examination must be undertaken. 中文

The proposed scheme for radium C' is arranged to include values of p up to 4 and therefore transitions of the type $q \rightarrow q-4$. These certainly do not, and the transitions $q \rightarrow q-3$ probably do not, fit into the allowed transitions of the proposed model with the simple interactions proposed. But such transitions can be present if there are terms in the interactions depending essentially on the co-ordinates of three or more particles, not reducible to sums of terms depending on the co-ordinates of only two. Such terms are to be expected in such a close configuration, though one would scarcely expect their effect to be so large. If the proposed scheme proves ultimately to be correct, one may hope to work back from the γ -ray intensities to some knowledge of the magnitude of these triple and higher interactions. 中文

To sum up, one may say that the scheme proposed by Rutherford and Ellis, so far as it has yet been closely analysed, *that is for frequencies only*, seems likely with trivial modifications to conform completely to the requirements of a simple quantum mechanical model so far as

these requirements can yet be foreseen. Such a model, however, will make fairly stringent demands on intensity ratios, and as yet no scheme has been proposed and tested with these in mind. One may hope that further work on these lines will prove fruitful. 中文

While these models may well be able to explain the complicated spectrum of radium C', it is well to remember that the corresponding spectrum of thorium C' is very much simpler and contains no families of γ -rays—except perhaps very faint ones—corresponding to those of radium C', which have been interpreted in the scheme as transitions $q \rightarrow q-2$, $q \rightarrow q-3$, and $q \rightarrow q-4$. It has of course, in addition, a very strong isolated γ -ray of very high frequency. If therefore in attempting to proceed with this analysis, which in any event I believe to be important, one is forced finally to conclude that such models will *not* explain the facts for radium C', there is no call for surprise or disappointment. It may still be that the proposed scheme of $q \rightarrow q-1$ transitions will account properly for the important *common* features of the γ -ray spectra of radium B, radium C', thorium C', and probably other nuclei. It is more than likely that the striking *differences* between the spectra of radium C' and thorium C' should be associated with the two extra free protons in radium C', the atomic weight of which is of the form $4n+2$, while that of thorium C', is $4n$. 中文

In the models suggested above, the effect of the protons has been ignored primarily because there seems at present no simple way of incorporating them. But it is clear that the general effect of free protons present in normal and excited states will be to cause the set of low frequency transitions $q \rightarrow q-1$ to be repeated again at higher frequencies but with the same dependence on q , the constant shift between the two sets representing an excitation energy for a proton.

中文

R. H. Fowler: Cromwell House, Trumpington, Cambridge, Aug. 14.

Reference:

1. *Proc. Roy. Soc., A*, **132**, 667 (1931).

原子核的量子力学模型

拉尔夫·福勒

到20世纪30年代时，物理学家们认为他们已经对原子核的结构非常了解了：原子核的质量由所包含的质子数决定，而质子的一部分电荷被 β 衰变中带负电的电子所中和。但是，即使这样，仍然不知道这么多相互排斥的质子怎样才能稳定地排布在一个非常狭小的空间中。在本文中，物理学家拉尔夫·福勒提出了一个能够解释这种稳定性的理论，该理论基于放射性原子会放出 α 粒子的实验证据。当然，正确的解释需要涉及另一种核粒子，即直到1932年才发现的中子。 [英文](#)

卢瑟福勋爵和埃利斯博士在他们最近发表的文章^[1]中指出，大量镭C'同位素放射出的 γ 射线可以用一种简单而有序的方法进行归纳，他们指出， γ 射线的多样性主要是由多个 α 粒子被激发到同一个激发态上，而不是由同一个 α 粒子被激发到多个激发态上造成的。他们对由镭C'放射出的 γ 射线进行归纳的方法也许并不是唯一可行的，但是任何适用的方法可能都会呈现出相同的特征。 [英文](#)

这样，我们就迫切地需要建立具有这种特征的模型并对模型进行细致的理论研究，这个模型可以是一个只有简单相互作用的模型，也可以是包含了大约50个 α 粒子的原子核模型。卢瑟福和埃利斯得出的关于 γ 射线的最主要的特征可以用以下的形式来表示：

$$h\nu = pE_0 - qE_1,$$

p 是一个取值从1到4的整数，而 q 是一个从0开始的整数，最大可能只能取到10；在镭C'同位素的衰变实验中， E_1 的取值大约是 E_0 取值的1/16，与镭B同位素衰变实验中相应的 E_1 值大致相当。对于镭C'同位素来说，我

们需要选取不同的 E_0 值。

英文

我们可以研究以下两个可能成功解释原子核稳定性的模型。第一个模型认为每个 α 粒子都可以在中心势场中独立运动（这个中心势场指的是与其他 α 粒子之间的复杂相互作用），而整个原子核又受到形式为 $V(r_{ij})$ 的微扰势场的影响，其中 $V(r_{ij})$ 是每对粒子中第 i 个 α 粒子和第 j 个 α 粒子之间的相互作用，其中 r_{ij} 是第 i 个 α 粒子和第 j 个 α 粒子之间的距离。这样的模型与包含电子的原子模型非常类似，不同的是 α 粒子的波函数是对称的，而不像电子的波函数那样是反对称的。这种本质上的区别允许原子核中的粒子发生重复激发，而原子中的电子是不可能出现重复激发的情况的。在初步的讨论中，我们可以把三维情况进一步简化到一维情况。

英文

第二个模型假设每对标记为 i, j 的 α 粒子对彼此有势能为 $\frac{1}{2}\lambda r_{ij}^2$ 的相互作用。很明显，这个模型对作用力所做的近似是一个非常不好的物理近似，但是这个近似的优点在于我们可以对其进行严格的计算而不只是用微扰理论来进行近似研究。关于以上这两个模型的研究已经开始，但到目前为止只完成了被简化到一维情况下的第一个模型。

英文

就像任何类似的合理模型那样，我们只把注意力集中到最普遍的特征上面来，并得到了以下的结果，这些结果在很大程度上和卢瑟福、埃利斯的构想十分吻合，但是似乎也明确说明我们需要建立一个更加精细的模型。模型中由多个 α 粒子跃迁到同一个激发态上所产生的能级具有这样的形式，即相应的 γ 射线（如果所有 γ 射线都被能放射出来）的频率大致为：

$$h\nu = p(E_0 - qE_1)$$

如果将卢瑟福与埃利斯的构想稍加修正，由此得出的射线频率将和上式中的射线频率吻合得很好。因此我们用频率关系对应于 $2(E_0 - qE_1)$ 和 $2(E'_0 - qE_1)$ 的两组 γ 射线代替以前提出的频率关系对应于 $2E_0 - qE_1$ 的单组 γ 射线，其中， E_0 和 E'_0 几乎相等。我们还用频率关系对应于 $3(E_0 - qE_1)$ 、 $3(E'_0 - qE_1)$ 和 $3(E''_0 - qE_1)$ 的三组 γ 射线来代替频率关系对应于 $3E_0 - qE_1$ 的单组 γ 射线，由此类推。此外，很明显地，当我们考虑三维情况下的该模型时，将会出现高能级的简并情况。并且，理论表明，比

值 E_0/E_1 在数值上应该略小于 $\frac{1}{2}n(=26)$ ，与我们在镭C'同位素中观察到的 E_0/E_1 值16相差得还不算太大。理论上还表明，不同的放射性原子核的 E_0 和 E_1 值（尤其是 E_1 的值）不会相差太多。在镭的C'和B同位素的观测结果中， E_1 的观测值的确相近，但是 E_0 的值却并非如此。而其他原子核放射出的 γ 射线还没有用这种方法分析过。 英文

所有这些特性都是很普遍的，并且我们得到的一致性结果也很有说服力。然而我们还可以进一步估算各种不同的 γ 射线的相对放射频率，这些不同的放射频率对应 α 粒子从 q 激发态到 $q-1$ ， $q-2$ ， $q-3$ 等激发态的跃迁。按照前面所提到的相互作用能量的表达形式， $q \rightarrow q-3$ 的跃迁过程应该不存在，即使存在也是非常罕见的，而 $q \rightarrow q-4$ ， $q \rightarrow q-5$ 等情况的跃迁过程也都不存在。理论上给出了 $q \rightarrow q-2$ 和 $q \rightarrow q-1$ 这两个跃迁发生频率的之比 R 的第一级近似形式：

$$R\left(\frac{q \rightarrow q-2}{q \rightarrow q-1}\right) = \frac{q-1}{6.5}f$$

式中的 f 因子一定小于单位1，但可能不太会小于1/10。高阶项对比值 R 的绝对值有很大的影响，所以如果上面提到的构想中相应的 R 值与实验结果不能严格一致时，我们也不必太在意。 R 的一个具有普遍重要性的特征是，它随着 q 的增大而增大。在对任何有效模型进行修正的时候，我们都必须记住 R 的这个特征。以上提到的所有特征到现在为止还不能确定是否可以整合到另一个令人满意的模型当中去，必须经过仔细地反复验证。 英文

以上提出的关于镭C'同位素的构想中， p 的取值可以从1到4，因此，构想中包含了 $q \rightarrow q-4$ 的跃迁。在前面提到的简单相互作用模型中 $q \rightarrow q-4$ 的跃迁肯定是被禁止的，而 $q \rightarrow q-3$ 的跃迁有可能被禁止。但是，如果相互作用项是由三个或者三个以上粒子的坐标所决定的，而且不能化简成只由两个粒子的坐标所决定的两体相互作用项的总和时，上面所说的 $q \rightarrow q-3$ 、 $q \rightarrow q-4$ 的跃迁就可能发生了。以上所讨论的相互作用项在形式上都很相近，我们想象不到这些相互作用项的影响会如此之大。如果上面提出的考虑三个粒子相互作用的构想最终被证明是正确的，那么我们也许可以回过头来，从 γ 射线的强度出发来获知这些三重或者多重相互作用的大小。 英文

总之，我们可以认为卢瑟福和埃利斯所提出的构想到现在为止已经被仔细地分析过了，这是只从频率的角度进行研究的，从这方面看，这一构想似乎经过细微的修正就可以完全符合可以预见的简单量子力学模型的要求。然而，这样的一个模型对强度比的要求非常严格，就我所知目前还没有人提出这方面的有关方案和检测方法。我们希望今后在这方面的研究工作能富有成效。

英文

虽然这些模型也许可以很好地解释镭C'的复杂谱线，但不要忘记，钍C'的对应谱线要简单得多，而且不包括镭C'谱线中那些由 $q \rightarrow q-2$ 、 $q \rightarrow q-3$ 、 $q \rightarrow q-4$ 跃迁所产生的 γ 射线族——除了几条非常微弱谱线以外。当然，钍C'的相应谱线中还包含了另外一条非常强的独立的高频 γ 射线。如果我们试图对以上现象继续进行分析（我认为这个分析无疑重要的），我们最终不得不得出这样的结论，适用于钍C'的模型将无法用来解释镭C'的实验事实，对于这个结果，我们大可不必感到惊讶或失望。上面提到的 $q \rightarrow q-1$ 的跃迁方案，仍然可以很好地解释镭B、镭C'、钍C'（可能还有其他的放射性原子核）衰变放射出的 γ 射线谱中共有的重要特征。更有可能发生的情况是，镭C'和钍C'谱线中惊人的差异应该与镭C'比钍C'多出两个自由质子有关。镭C'的原子量是 $4n+2$ ，而钍C'的原子量是 $4n$ 。

英文

在上面所提出的模型中，质子的效应从一开始就被忽略了，因为目前似乎还没有将质子效应整合到模型中的简单方法。但是可以明确的是，在正常态和激发态，由自由质子所引发的普遍效应会使低频跃迁 $q \rightarrow q-1$ 在高频情况下重复发生，但是高频情况下的跃迁同样依赖于 q ，两种情况下的常数变化代表了一个质子的激发能。

英文

（王静 翻译；李军刚 审稿）

The Angular Momentum of Light

C. V. Raman

Arthur Compton's pioneering work on the scattering of light by electrons showed how the process could be understood in quantum terms as a collision conserving energy and momentum. As Raman argues here, the scattering of light from molecules is considerably more complicated, since the photon may excite molecular internal degrees of freedom such as rotations or vibrations. If the intrinsic angular momentum of a photon may only take certain discrete values, this would account for a known "selection rule" governing the permitted changes in molecular angular momentum during light scattering. It also implies that any change in molecular angular momentum must be accompanied by a reversal of the circular polarisation of the photon, as confirmed by recent experiments in Calcutta.

[中文](#)

THE work of Compton on X-ray scattering led to the general acceptance of the idea that the scattering of radiation by a material particle is a unitary process in which energy and linear momentum are conserved. A molecule is, however, a much more complicated structure than an electron, and the conservation principles by themselves would give us an erroneous idea of what we should expect in light-scattering. This follows from the fact that a molecule has in general three degrees of freedom of rotation, several degrees of

freedom of vibration according to its complexity, and various possible modes of electronic excitation, and that each of these may correspond to one or other of an extended series of quantum numbers. Restricting ourselves to the cases in which the molecule takes up a part of the energy of the quantum, the conservation principles would indicate that the spectrum of the scattered light should contain an immense number of new lines. [中文](#)

Actually, a remarkable simplicity characterises the observed spectra of the light scattered by polyatomic molecules, a simplicity which is in striking contrast with the complexity of their absorption and emission spectra. It is clear that the Compton principles cannot be regarded as capable of *predicting* the observed phenomena of light-scattering, and that their utility lies solely in the *interpretation* of results discovered by experiment. These remarks seem necessary to correct an impression to the contrary which finds expression in some recent publications.

[中文](#)

We may extend Compton's principle and add angular momentum to the quantities which we should expect to find conserved in the collision between a light-quantum and a molecule. The fact that, in liquids and solids, the mutual influence of the material particles is very considerable, attaches some uncertainty to the interpretation of the results obtained with them. The recent success of Bhagavantam at Calcutta in measuring the polarisation and intensity of light scattered by gases, however, opens up new possibilities for the development of the subject. [中文](#)

As a working hypothesis, we may follow Dirac and assume that the angular momentum of a photon is *plus* or *minus* $h/2\pi$, intermediate values being inadmissible. This supposition enables us to interpret very simply the known selection rule $\Delta m = 0$ or ± 2 for the change of rotational quantum number of a diatomic molecule in light-scattering, which follows as a natural consequence of it. Further, it follows¹ that

a change in rotational quantum number of the molecule should be accompanied by a reversal in the sign of circular polarisation of the photon, when the latter is scattered in the forward direction. This reversal has been actually observed by Bär and by Bhagavantam with the rotational wings accompanying the original mercury lines scattered in liquids, and the data obtained by Bhagavantam with hydrogen gas may also be interpreted as a confirmation of the same result. [中文](#)

It is remarkable that the latter result is also predicted by the classical electromagnetic theory of light for the case of a rotating anisotropic particle scattering circularly polarised radiation. Nevertheless, it is clear that the observed phenomena may be regarded as an experimental proof that radiation has angular momentum associated with it, and that it has the values $\pm h/2\pi$ for each quantum. [中文](#)

(128, 545; 1931)

C. V. Raman: 210 Bowbazar Street, Calcutta, Aug. 15.

Reference:

1. *Nature*, **128**, 114 (July 18, 1931).

光的角动量

钱德拉塞卡拉·文卡塔·拉曼

阿瑟·康普顿在研究电子对光的散射时发现这个过程可以用量子力学中保持能量和动量守恒的碰撞理论来解释。就像拉曼在这里指出的那样，分子对光的散射更加复杂，因为光子可以激发分子内部的自由度，如旋转或者振动。如果一个光子的内禀角动量只能取某些不连续的值，那么这就解释了为什么普遍认可的“选择定则”能够支配分子角动量在光散射过程中可能出现的变化。最近在加尔各答的实验证明：分子角动量的任何变化都将伴随着光子圆偏振的反转。

[英文](#)

康普顿关于X射线散射的研究使人们普遍地接受了以下观点，即物质粒子对辐射的散射是一种维持能量和线性动量守恒的么正过程。然而，一个分子的结构比一个电子的结构要复杂得多，而守恒定理本身使我们在预测光散射的结果时会出现错误。这是因为一个分子通常具有三个转动自由度、几个振动自由度（数量与它的复杂程度有关）以及多种电子激发的可能模式，每一种模式都可能对应于一个或另一个来自扩展系列的量子数。如果我们局限于认为分子占据量子能量的一部分，那么根据守恒原理，散射光的谱就应该包含数量巨大的新线。

[英文](#)

实际上我们所观察到的多原子分子散射光的谱非常简单，要比它们的吸收谱和发射谱简单很多。显然，康普顿原理不能预言观察到的光散射现象，它们只能用于解释由实验得到的结果。上述意见对于修正最近一些刊物中出现的相反看法是很有必要的。

[英文](#)

我们可以拓展康普顿原理，并把角动量加入到我们认为在光量子与分子发生碰撞时应该保持守恒的量当中。在液体和固体中，物质粒子之间的相互影响相当可观，因而对散射结果的解释会带有某种不确定性。

巴加万塔姆最近在加尔各答成功地测量了光被气体散射时的偏振性和强度，该成果为这项课题的研究开辟了新的可能性。 [英文](#)

在对这一假设进行推导时，我们可以根据狄拉克的理论假定一个光子的角动量为 $\pm h/2\pi$ ，中间值的存在是不允许的。这个假定能使我们很简单地解释为什么双原子分子在光散射中转动量子数的改变要遵循选择定则 $\Delta m = 0$ 或 ± 2 ，这样选择定则的出现就成为了一个自然而然的结果。此外我们还发现^[1]：当光子向前散射时，分子转动量子数的变化应伴随着光子圆偏振符号的反向。巴尔和巴加万塔姆用伴随在液体中散射的原来汞线的旋转两翼观测到了这一反向现象，巴加万塔姆用氢气得到的数据也可以用来证明同样的结论。 [英文](#)

值得注意的是，后一个结果也可以在旋转的各向异性并具有圆偏振散射线粒子的情况下由光的经典电磁理论推导出来。显然观测到的现象也可以作为辐射具有相关角动量的实验证据，而每个量子所具有的角动量大小为 $\pm h/2\pi$ 。 [英文](#)

（沈乃澂 翻译；张泽渤 审稿）

Isolated Quantised Magnetic Poles

O. W. Richardson

There were, in classical physics, no “magnetic charges”—no isolated magnetic poles without their complementary pole. But Paul Dirac suggested that quantum theory might allow the existence of such “monopoles”, and here distinguished British physicist Owen Willans Richardson speculates on what their existence might entail for physics. While science focused on atoms made of electrically charged particles, a similar hierarchy of magnetic atoms might exist. Richardson argues that their properties would be unusual; in particular, the frequencies of their spectral lines would be some 10^{10} higher than for “ordinary” matter. Dirac had speculated that the forces between magnetic monopoles would prevent their separation in ordinary circumstances, but Richardson suggests this might happen for cosmic rays of extremely high energy. [中文](#)

IN the last number of the *Proceedings of the Royal Society*, Dirac has come to the conclusion that the quantum theory requires the existence of discrete magnetic poles of a strength equal to $137 \div 2$ times the electronic charge. If such objects were common one might expect the universe to be a good deal different from what experimenters have found it to be, so far. [中文](#)

There seems no a priori reason why the whole theory of atom building which has been built up for electrons and nuclei—an electrostatic problem apart from details—should not be carried over bodily into the corresponding magneto-static problem of the attractions of the oppositely charged poles. In this way we might, at first, expect to get a set of “magnetic” atoms, similar to the electric atoms of which matter is generally supposed to be built up. These atoms would be a good deal different from those we think we are familiar with. How much different depends to some extent on what the mass of a magnetic pole is. The quantum theory does not tell this, but I think its value, if it exists, can be fixed by an argument based on classical ideas at about 500 times that of the corresponding electronic object. Following this general line of argument, the dimensions of these magnetic atoms come out at 10^{-14} cm. to 10^{-15} cm. compared with 10^{-7} cm. to 10^{-8} cm. for the atoms of the periodic table. The frequencies of the “spectral” lines emitted by these magnetically constructed atoms would run about 10^{10} times those of the corresponding lines of the electronic spectra; for example, the first line of the Lyman series would be raised from $\nu = 2.5 \times 10^{15}$ to $\nu = 3.1 \times 10^{25}$ sec.⁻¹ if the corresponding states are capable of existence. Even if quite large changes are made in the mass of the magnetic poles, which is the doubtful element, the corresponding numbers will still remain quite wide apart. [中文](#)

Dirac has suggested that the reason these magnetic poles have not been observed may be that the forces between them are so much larger than those between electrons and protons that they cannot be separated. There is reason for believing they could not get together to the extent indicated by the preceding numbers. The number of kinds of atoms with azimuthal quantum number 1 which can be formed from these magnetic units is much less than unity. This follows from Dirac’s formula for the spectral terms for hydrogen, or alternatively, from the principle of minimum time. This may be forcing the required

atoms too much into the pattern of those with which we are familiar. In any event, no atom with azimuthal quantum number less than $34\frac{1}{4}$ can be made out of these elements. Otherwise the time factors in the wave functions involve real exponentials and become infinite with lapse of time. However, even with such high quantum numbers the forces would still be enormous compared with those in corresponding electronic structures and the frequencies would still be quite high.

中文

There may be an application of these products of the quantum theory in the field of “ultra-penetrating” radiations. I have no first-hand knowledge of the process of creation, but I should suspect it would be relatively difficult to create objects with the intrinsic energy of these magnetic poles. It seems likely, therefore, that their abundance would be very small compared with that of electrons and protons, but there might be enough in the universe to account for such ultra-penetrating radiations as are not capable of being accounted for otherwise. The possible existence of such isolated magnetic poles, with properties so very different from those of electrons and protons, obviously changes the basis for discussion of a good many cosmological questions. 中

文

(128, 582; 1931)

O. W. Richardson: King's College, London, W.C.2, Sept. 18.

孤立的量子化磁极

欧文·威兰斯·里查孙

在经典物理学中不存在“磁荷”这个概念——没有相反磁极的孤立磁极是不存在的。但保罗·狄拉克提出量子理论也许能允许这样的“磁单极”存在。在本文中，英国著名物理学家欧文·威兰斯·里查孙认为对于物理学来说磁单极的存在也许是必然的。既然科学主要研究由带电的粒子组成的原子，就应该有相应的带磁性的一类原子存在。里查孙指出它们的性质很不一般；尤其是它们的谱线频率是“普通”物质的 10^{10} 倍。狄拉克推测磁单极之间的强大作用力使它们在通常环境下无法分离，但里查孙认为在**高能宇宙射线**中这种现象就有可能会发生。 [英文](#)

在最近一期的《皇家学会会刊》中，狄拉克已得出结论，量子理论要求存在强度相当于 $137 \div 2$ 倍的电子电荷的单个磁极。假如这样的物质是普遍存在的，那么我们可以预期现实的宇宙与目前实验者们眼中的宇宙会有很大的不同。 [英文](#)

似乎没有理由不能把建立在电子和原子核之上的一整套原子理论——除细节外基本属于静电问题——应用到以相反磁荷相互吸引为基础的相应的静磁问题上。按照这种方式，我们首先可以预期得到一组与带电原子类似的“磁”的原子，通常我们认为物质是由带电原子构成的。磁的原子与我们原有概念中所熟知的原子有很大的差别。差别的大小在某种程度上取决于磁极的质量。量子理论并未说明相应的具体数值，但我认为如果这个值存在，用经典方法论证则应该约为相应带电物的500倍。按照这个思路推算，这些磁的原子的尺度达到 10^{-14} cm至 10^{-15} cm，而元素周期表中的原子尺度为 10^{-7} cm至 10^{-8} cm。由这些磁性结构原子发射的“谱”线频率约为带电原子谱线相应频率的 10^{10} 倍；例如，假

如以上磁性结构的原子是存在的，赖曼线系中的第一条线的频率将从 $\nu = 2.5 \times 10^{15} \text{ s}^{-1}$ 增加至 $\nu = 3.1 \times 10^{25} \text{ s}^{-1}$ 。即使对数值不确定的磁极质量作很大的调整，所得的结果仍与带电原子的情况相差很大。 [英文](#)

狄拉克指出，这些磁极尚未被观测到的原因可能是因为它们之间的力远大于电子和质子之间的力，从而使它们不能分离。我们有理由相信它们不可能接近到上述数字表示的程度。这些磁单元形成的角量子数为1的原子种类数远小于1。这是根据与氢光谱项有关的狄拉克公式或者根据最小时间原理得出的。这也许是在迫使磁的原子过于符合我们所熟悉的模式。在任何情况下，磁的原子都不能构成角量子数小于 $34\frac{1}{4}$ 的原子。否则，波函数中的时间因子会含有实指数，并随时间的消逝而趋于无限大。然而，尽管有如此高的量子数，与相应的电子结构相比，磁单元之间的作用力仍然很大，频率也仍然很高。 [英文](#)

这些量子理论的成果可能会在“超穿透”辐射领域中得到应用。我对孤立磁极的形成过程没有直接的了解，但我推测，产生这种具有磁极内能的物质是相当困难的。因此，地球上磁原子的数量似乎应该远小于电子和质子的数量，但在宇宙中磁原子的数量也许已经足以用来解释超穿透辐射这种不能用其他方法解释的现象。如果这类与电子和质子的性质差异很大的孤立磁极是存在的，那么将会使许多宇宙问题的研究思路发生明显的变化。 [英文](#)

（沈乃澂 翻译；赵见高 审稿）

Maxwell and Modern Theoretical Physics*

N. Bohr

On the occasion of the Maxwell Centenary Celebrations in Cambridge, October 1931, Niels Bohr presented an address on Maxwell and Modern Theoretical Physics. Bohr notes that Maxwell's theory of electricity and magnetism had made possible developments in the understanding of atomic matter, and also provided the foundations for the discovery of quantum theory. Although this theory moved beyond Maxwell's ideas, analysis in quantum theory still required Maxwell's theory, especially through the relations for the energy and momentum of light quanta. Bohr asserts that Maxwell's theory will always play a central role in physics, as the formulation of the laws of quantum physics depends on the existence of a classical world describable in Maxwell's terms. [中文](#)

I feel greatly honoured in being given this opportunity of paying a tribute of reverence to the memory of James Clerk Maxwell, the creator of the electromagnetic theory, which is of such fundamental importance to the work of every physicist. In this celebration we have heard the Master of Trinity and Sir Joseph Larmor speak, with the greatest authority and charm, of Maxwell's wonderful discoveries and personality, and of the unbroken tradition upheld here in Cambridge connecting his life and his work with our time. Although I have had

the great privilege, in the years of my early studies, of coming under the spell of Cambridge and the inspiration of the great English physicists, I fear that it may not be possible for me to add anything of sufficient interest in this respect, but it gives me very great pleasure indeed to be invited to say a few words about the relation between Maxwell's work and the subsequent development of atomic physics.

中文

I shall not speak of Maxwell's fundamental contributions to the development of statistical mechanics and of the kinetic theory of gases, which Prof. Planck has already discussed, especially as regards Maxwell's fruitful co-operation with Boltzmann. It is only my intention to make a few remarks about the application of the electromagnetic theory to the problem of atomic constitution, where Maxwell's theory, besides being extremely fruitful in the interpretation of the phenomena, has yielded the utmost any theory can do, namely, to be instrumental in suggesting and guiding new developments beyond its original scope. 中文

I must, of course, be very brief in commenting upon the application of Maxwell's ideas to atomic theory, which in itself constitutes a whole chapter of physics. I shall just recall how successfully the idea of the atomic nature of electricity was incorporated into Maxwell's theory by Lorentz and Larmor, and especially how it furnished an explanation of the dispersion phenomena, including the remarkable features of the Zeeman effect. I would also like to allude to the important contribution to the electron theory of magnetism made by Prof. Langevin, whom we much regret not to be able to hear today. But above all, I think in this connexion of the inspiration given by Maxwell's ideas to Sir Joseph Thomson in his pioneer work on the electronic constitution of matter, from his early introduction of the fundamental idea of the electromagnetic mass of the electron, to his famous method, valid to this day, of counting the electrons in the

atom by means of the scattering of Röntgen rays.

[中文](#)

The developments of the atomic theory brought us soon, as everybody knows, beyond the limit of direct and consistent application of Maxwell's theory. I wish to emphasise, however, that it was just the possibility of analysing the radiation phenomena provided by the electromagnetic theory of light which led to the recognition of an essentially new feature of the laws of Nature. Planck's fundamental discovery of the quantum of action has necessitated, indeed, a radical revision of all our concepts in natural philosophy. Still, in this situation, Maxwell's theory continued to provide indispensable guidance. Thus the relation between energy and momentum of radiation, which follows from the electromagnetic theory, has found application even in the explanation of the Compton effect, for which Einstein's idea of the photon has been so appropriate a means of accounting for the marked departure from the classical ideas. The use of Maxwell's theory as a guide did not fail either in the later stage of atomic theory. Although Lord Rutherford's fundamental discovery of the atomic nucleus, which brought our picture of the atom to such wonderful completion, showed most strikingly the limitation of ordinary mechanics and electrodynamics, the only way to progress in this field has been to maintain as close contact as possible with the classical ideas of Newton and Maxwell.

[中文](#)

At first sight it might perhaps look as if some essential modification of Maxwell's theory was needed here, and it has even been suggested that new terms should be added to his famous equations for electromagnetic fields in free space. But Maxwell's theory has proved far too consistent, far too beautiful, to admit of a modification of this kind. There could only be a question, indeed, of a generalisation of the whole theory, or rather of a translation of it into a new physical language, suited to take into account the essential indivisibility of the elementary processes in such a way that every feature of Maxwell's

theory finds a corresponding feature in the new formalism. In the last few years, this aim has actually been attained to a large extent by the wonderful development of the new quantum mechanics or quantum electrodynamics, connected with the names of de Broglie, Heisenberg, Schrödinger, and Dirac. [中文](#)

When one hears physicists talk nowadays about “electron waves” and “photons”, it might perhaps appear that we have completely left the ground on which Newton and Maxwell built; but we all agree, I think, that such concepts, however fruitful, can never be more than a convenient means of stating characteristic consequences of the quantum theory which cannot be visualised in the ordinary sense. It must not be forgotten that only the classical ideas of material particles and electromagnetic waves have a field of unambiguous application, whereas the concepts of photons and electron waves have not. Their applicability is essentially limited to cases in which, on account of the existence of the quantum of action, it is not possible to consider the phenomena observed as independent of the apparatus utilised for their observation. I would like to mention, as an example, the most conspicuous application of Maxwell’s ideas, namely, the electromagnetic waves in wireless transmission. It is a purely formal matter to say that these waves consist of photons, since the conditions under which we control the emission and the reception of the radio waves preclude the possibility of determining the number of photons they should contain. In such a case we may say that all trace of the photon idea, which is essentially one of enumeration of elementary processes, has completely disappeared. [中文](#)

For the sake of illustration, let us imagine for a moment that the recent experimental discoveries of electron diffraction and photonic effects, which fall in so well with the quantum mechanical symbolism, were made before the work of Faraday and Maxwell. Of course, such a situation is unthinkable, since the interpretation of the experiments in

question is essentially based on the concepts created by this work. But let us, nevertheless, take such a fanciful view and ask ourselves what the state of science would then be. I think it is not too much to say that we should be farther away from a consistent view of the properties of matter and light than Newton and Huygens were. We must, in fact, realise that the unambiguous interpretation of any measurement must be essentially framed in terms of the classical physical theories, and we may say that in this sense the language of Newton and Maxwell will remain the language of physicists for all time. 中文

I do not think that this is a proper occasion to enter into further details regarding these problems, and to bring new views under discussion. In conclusion, however, I am glad to give expression to the great expectation with which the whole scientific world follows the exploration of an entirely new field of experimental physics, namely, the internal constitution of the nucleus, which is now carried on in Maxwell's laboratory, under the great leadership of the present Cavendish professor. In the fact that nobody here in Cambridge is likely to forget Newton's and Maxwell's work, we see perhaps the very best auguries for the continued success of these endeavours. Even if we must be prepared for a still further renunciation of ordinary visualisation, the basic concepts of physics which we owe to the great masters will certainly prove indispensable in this new field as well.

中文

(128, 691-692; 1931)

* Address delivered on the occasion of the Maxwell Centenary Celebrations at Cambridge on Oct. 1.

麦克斯韦与现代理论物理*

尼尔斯·玻尔

1931年10月，剑桥大学举行了麦克斯韦诞辰一百周年纪念会，尼尔斯·玻尔在会上发表了一篇有关麦克斯韦和现代理论物理的演讲。玻尔指出麦克斯韦的电磁学理论为人类了解原子世界作出了贡献，也为创立量子理论提供了基础。虽然量子理论超越了麦克斯韦的学说，但量子力学中的分析手段离不开麦克斯韦的理论，尤其是在建立光量子能量和动量之间的关系时。玻尔认为麦克斯韦的理论在物理学中的核心地位不会丧失，因为量子物理定律中的公式都是按照麦克斯韦所描述的经典世界创建的。 [英文](#)

我非常荣幸能有机会在此表达我对电磁学理论的创立者——詹姆斯·克拉克·麦克斯韦的敬意，因为电磁学理论对每一位物理学家的研究工作都是非常重要的。在这个纪念庆典上，三一学院院长和约瑟夫·拉莫尔爵士已经给我们作了最具权威性的精彩演讲，介绍了麦克斯韦的重要发现和伟大人格，还提到剑桥大学一直坚持把麦克斯韦的生活与工作和我们所处的时代紧密相连的传统。尽管我早年曾有幸在剑桥大学工作过一段时间，也接受过知名英国物理学家们的指点，但在这方面我恐怕讲不出更多吸引人注意的内容，不过我仍然非常高兴能应大会之邀来这里简单介绍一下麦克斯韦的研究与随后发展起来的原子物理之间的关系。

[英文](#)

我不打算讲麦克斯韦对统计力学和气体动力学的重大贡献，因为普朗克教授已经在前面介绍过了，他还特别提到麦克斯韦和玻尔兹曼曾经一起进行过有效合作。在这里我只想谈一下如何应用电磁学理论解决原子的构成问题，在这个问题上，麦克斯韦的理论不仅很好地解释了相关的实验现象，而且已经达到了理论所能达到的极致，因为它可以启发和

引导自身领域之外的研究工作的发展。

[英文](#)

当然，我只能非常简短地介绍麦克斯韦理论在原子物理中的应用，因为仅这个问题本身就足以构成物理学中整整一章的内容。我要说洛伦兹和拉莫尔将电的原子本质与麦克斯韦理论结合在一起的思想非常成功，特别是由此可以解释包括塞曼效应的显著特征在内的色散现象。我还想提及朗之万教授在磁性的电子理论方面所作的贡献。遗憾的是，他今天不能到场为我们作报告。但我认为最值得一提的是约瑟夫·汤姆逊爵士在物质电子结构方面的开拓性工作一直受到麦克斯韦理论的启发，从他早期引入电子电磁质量这一基本概念，到后来他发明用伦琴射线的散射计算原子中电子数的方法，这种方法一直沿用至今。

[英文](#)

我们都知道，原子理论的迅速发展使我们现在已经不能再像原来那样直接利用麦克斯韦的理论来解决原子内部的问题。但我要强调的是，正是因为有了光的电磁学理论，我们才可能去分析辐射现象，才可能认识到自然法则的一个全新特征。的确，普朗克关于量子行为的重要发现使我们必须从根本上修正自然科学中的所有观念。但即便如此，麦克斯韦的理论仍然能为我们的研究工作提供必不可少的指导。由电磁学理论可以推出辐射能量与动量之间的关系，而我们可以利用这种关系来解释康普顿效应，虽然爱因斯坦的光子理论明确指出康普顿效应与经典理论之间存在着明显的区别。麦克斯韦的理论在原子理论后来的发展中仍然具有一定的指导意义。尽管卢瑟福勋爵对原子结构的完整描述说明普通力学和电动力学具有极大的局限性，但想在这一领域进一步拓展就必须尽可能紧密地联系牛顿和麦克斯韦的经典理论。

[英文](#)

乍看起来，我们似乎需要从本质上对麦克斯韦的理论进行修正，甚至有人指出，应该在麦克斯韦著名的自由空间电磁场方程中加入新项。但麦克斯韦的理论高度自洽非常完美，人们无法对它进行这样的修正。实际上，我们只能对整个理论进行一致化处理，更确切地说就是把麦克斯韦的方程翻译成一种新的物理语言，这种新语言通过为麦克斯韦理论中的每一个特征找到其在新形式下的对应特征来反映基本物理过程中的不可分性。前一段时间，德布罗意、海森堡、薛定谔和狄拉克在量子力学或电动力学方面所取得的突破性进展已经在很大程度上实现了上述目标。

[英文](#)

今天，当我们听到物理学家们谈论“电子波”和“光子”的时候，这些概念似乎已经完全脱离了牛顿和麦克斯韦建立起来的理论基础；但是我认为，大家都会同意这样一个观点：这些新观念虽然发挥了很大的作用，但它们不过是一种用来说明量子理论特殊性的便捷方法，缺乏一般意义上的形象化特征。不要忘记，只有关于物质粒子和电磁波的经典观念得到了实际的应用，而光子和电子波的概念还没有应用到实践中。应用受到限制的主要原因是由于存在量子效应，不可能认为观察到的现象与所用的仪器无关。作为一个例子，我想谈一下麦克斯韦理论最著名的应用，也就是在无线电传输领域中的应用。认为电磁波由光子组成只不过是形式上的说法而已，因为我们在发射和接收电磁波的时候是无法确定电磁波中包含的光子数目的。因此我们可以说，以计数为本质的光子概念已经彻底不复存在了。

英文

为了进一步说明问题，我们可以想象一下如果严格符合量子力学规律的电子衍射和光子效应是在麦克斯韦和法拉第的工作问世之前就已经发现了，那将出现什么样的情况呢？当然，这种情况是不可能出现的，因为用来解释以上实验发现的理论是以麦克斯韦和法拉第这两人的理论成果为依据的。不过，我们还是可以发挥一下我们的想象力，问问自己，如果没有麦克斯韦和法拉第的理论，科学会处于一个什么样的水平。我想如果说我们应该在牛顿和惠更斯认为光是一种物质的理论上加以拓展，这并不为过。事实上，我们应该意识到的是，对任何测量结果的准确解释都必须建立在经典物理理论的框架之内，从这个意义上我们可以说，牛顿和麦克斯韦的语言仍将是物理学家们的通用语言。

英文

我认为现在不是继续深入讨论这些问题并在讨论中引入新观点的最好时机。但在最后我想说的是，目前麦克斯韦实验室正在现任的卡文迪什教授的领导下开展原子核内部结构方面的研究，我希望整个科学界都去探索这一全新的实验物理领域。事实上，我相信在座的剑桥大学同仁们都不会忘记牛顿和麦克斯韦的工作，也许我们已经看到利用这些成果最有可能取得后续的成功。就算我们必须做好进一步放弃常规理论的准备，大师们为我们总结的这些基本物理观点在这个新领域中也将被证明是必不可少的。

英文

* 这是1931年10月1日在剑桥举行的麦克斯韦诞辰一百周年庆祝大会上玻尔所作的演讲。

Experimental Proof of the Spin of the Photon

C. V. Raman and S. Bhagavantam

Chandrasekhara Venkata Raman and S. Bhagavantam had recently presented experimental evidence suggesting that the photon carries one unit of intrinsic angular momentum. In subsequent weeks, great improvements in their technique led to much more accurate results, which they now report. Their experiments involved measuring the depolarisation of the light scattered in a fluid. By eliminating a source of error in the previous experiments, due to light scattered from the walls of the containing vessels, they were able to show that a theory based on photons carrying quantum-mechanical spin 1 accounted for the results far more accurately than an alternative theory for spinless photons. [中文](#)

IN a paper under this title which has recently appeared,¹ we have described and discussed observations which have led us to the conclusion that the light quantum possesses an intrinsic spin equal to one Bohr unit of angular momentum. In the four weeks which have elapsed since that paper was put into print, the experimental technique has been much improved in the direction of attaining greater precision. It appears desirable forthwith to report our newer results, which confirm the conclusion stated above. [中文](#)

As mentioned in earlier communications,² the experiment we set

before ourselves was to determine the extent to which the depolarisation of Rayleigh scattering of monochromatic light is diminished when it is spectroscopically separated from the scattering of altered frequency arising from the molecular rotation in a fluid. An important improvement on our previous arrangements is the use of a pointolite mercury arc, which enables an intense beam of monochromatic light to be obtained which is rigorously transverse to the direction of observation. In the case of the feeble scattering by gases, a serious source of error is the parasitic illumination from the walls of the containing vessel. We have succeeded in eliminating this by using the gas under pressure in a steel cross with suitable arrangements for securing a dark background. The depolarisation of the scattered light is determined photographically with a spectrograph and a large nicol placed in front of the slit. The use of Schwarzschild's formula for photographic blackening enables the ratio of the horizontal and vertical components of scattered light to be calculated from the times of exposure in the two positions of the nicol which give equal densities in the spectra. [中文](#)

Using alternately a fine slit and a very broad slit on the spectrograph, the depolarisations of the Rayleigh scattering and of the total scattering respectively are determined. The following table gives the values for the case of oxygen, carbon dioxide, and nitrous oxide gases under pressure.

Table: Depolarisation percent

Gas	Observed		Calculated	
	Total Scattering	Rayleigh Scattering	Kramers-Heisenberg Theory	Spin Theory
O ₂	6.5	4.1	1.7	4.2
CO ₂	10.3	6.3	2.8	6.7
N ₂ O	12.0	7.7	3.4	7.9

[中文](#)

The depolarisations of the total scattering given in column 1 thus

found spectroscopically are in good agreement with the best accepted values determined by other methods. Column 2 gives the observed depolarisations of the Rayleigh scattering, column 3 the values calculated from the Kramers–Heisenberg dispersion theory, and column 4 the values calculated from the theory of the spinning photons discussed in our paper. It will be seen that the values given by the latter are strikingly supported by the experimental results. 中文

(129, 22-23; 1932)

C. V. Raman and S. Bhagavantam: 210 Bowbazar Street, Calcutta, India, Nov. 29.

References:

1. *Ind. Jour. Phy.*, **6**, 353 (Oct. 1931).
2. *Nature*, **128**, 576 and 727 (1931).

光子自旋的实验证据

拉曼，巴加万塔姆

钱德拉塞卡拉·文卡塔·拉曼和巴加万塔姆最近公布的实验结果证明光子带有一个单位的内禀角动量。在随后的几周内，他们通过改进实验技术得到了更为精确的结果，本文中报告了这些结果。他们用实验测量了光散射在一种液体中的解偏振现象。他们在去除了以前实验中由于容器壁的光散射所造成的误差之后指出：用假设光子在量子力学中的自旋为1的理论来解释实验结果要比假设光子没有自旋的理论更精确。 [英文](#)

我们在最近发表的一篇同名文章中^[1]，描述并讨论了我们的实验结果，即光量子具有一个玻尔角动量单位的内禀自旋。从那篇文章发表到现在已经过去4周，我们的实验技术在得到更高的精确度方面又有了很大改进。我们似乎有必要立即把最新的实验结果发表出来，而这新的实验结果也证实了上述结论。 [英文](#)

如从前的文章所提到的那样^[2]，用光谱法可以将单色光的瑞利散射从液体中由分子转动产生的变频散射中分离出来，我们的实验就是要确定瑞利散射解偏振降低的程度。我们对以前实验装置的一个重要改进是使用了汞弧光点光源，这样我们就可以得到一束与观察者方向严格垂直的高强度单色光。在气体散射很弱的情况下，由容器壁产生的寄生亮度将导致严重的实验误差。我们通过将钢的十字形腔中对气体加压，而这种十字形腔可用适当方式确保处于黑暗的背景中，从而成功地降低了这种误差。利用放置于狭缝前的一个大号尼科尔棱镜和光谱仪，我们可以用照相法将散射光解偏振的数值确定下来。根据底片黑度的史瓦西公式，我们可用尼科尔棱镜上产生相同光谱强度的两个不同位置的曝光次数计算出散射光横向偏振分量和纵向偏振分量的比值。 [英文](#)

在光谱仪上交替使用窄缝和宽缝，可以分别得到瑞利散射和总散射的解偏振百分比率。下表给出了O₂、CO₂以及N₂O气在加压条件下的相关数据：

表：解偏振百分比率

气体	观测值		计算值	
	总散射	瑞利散射	克拉莫－海森堡理论	自旋理论
O ₂	6.5	4.1	1.7	4.2
CO ₂	10.3	6.3	2.8	6.7
N ₂ O	12.0	7.7	3.4	7.9

英文

我们在第一列中给出了用光谱学方法观测得到的总散射解偏振比率，其数值与用其他方法得到的最佳结果十分吻合。第二列中给出的是观测到的瑞利散射解偏振比率，第三列是根据克拉莫－海森堡色散理论计算得到的数值，而第四列中的数据是由我们文章中讨论的光子自旋理论计算出来的。可以看到，第二种理论给出的数值与实验结果非常一致。

英文

（王静 翻译；赵见高 审稿）

The Decline of Determinism*

A. Eddington

Ten years ago, Arthur Eddington claims here, practically every notable physicist was a determinist, at least regarding physical processes. Physicists believed they possessed a powerful scheme of causal scientific law, embodied especially in classical mechanics, and saw the project of science as explaining ever more phenomena within this scheme. The quantum theory has now changed all this, stimulating reactions ranging from incredulity and cynicism to yawning indifference. Eddington argues, however, that the new indeterministic theory cannot be considered to be a rejection of the scientific method. He compares the older deterministic or “primary” laws to a scientific gold standard, now replaced by a “secondary” currency. Most other physicists now wonder why those primary laws were once accorded such reverence. [中文](#)

DETERMINISM has faded out of theoretical physics. Its exit has been commented on in various ways. Some writers are incredulous, and cannot be persuaded that determinism has really been eliminated. Some think that it is only a domestic change in physics, having no reactions on general philosophic thought. Some imagine that it is a justification for miracles. Some decide cynically to wait and see if determinism fades in again. [中文](#)

The rejection of determinism is in no sense an abdication of scientific

method; indeed it has increased the power and precision of the mathematical analysis of observed phenomena. On the other hand, I cannot agree with those who belittle the general philosophical significance of the change. The withdrawal of physical science from an attitude it has adopted consistently for more than two hundred years is not to be treated lightly; and it involves a reconsideration of our views with regard to one of the perplexing problems of our existence. In this address, I shall deal mainly with the physical universe, and say very little about mental determinism or freewill. That might well be left to those who are more accustomed to arguing about such questions, if only they could be awakened to the new situation which has arisen on the physical side. At present I can see little sign of such an awakening. [中文](#)

Definitions of Determinism

Let us first be sure that we agree as to what is meant by determinism. I quote three definitions or descriptions for your consideration. The first is by a mathematician (Laplace):

We ought then to regard the present state of the universe as the effect of its antecedent state and the cause of the state that is to follow. An intelligence, who for a given instant should be acquainted with all the forces by which Nature is animated and with the several positions of the entities composing it, if, further, his intellect were vast enough to submit those data to analysis, would include in one and the same formula the movements of the largest bodies in the universe and those of the lightest atom. Nothing would be uncertain for him; the future as well as the past would be present to his eyes. The human mind in the perfection it has been able to give to astronomy affords a feeble outline of such an intelligence. ... All its efforts in the search for truth tend to approximate without limit to the intelligence we have just imagined. [中文](#)

The second is by a philosopher (C. D. Broad):

“Determinism” is the name given to the following doctrine. Let S be any substance, ψ any characteristic, and t any moment. Suppose that S is in fact in the state δ with respect to ψ at t . Then the compound supposition that everything else in the world should have been exactly as it in fact was, and that S should have been in one of the other two alternative states with respect to ψ is an impossible one. [The three alternative states (of which δ is one) are to have the characteristic ψ , not to have it, and to be changing.] 中文

The third is by a poet (Omar Khayyám):

With Earth's first Clay They did the Last Man knead,
And there of the Last Harvest sow'd the Seed:
And the first Morning of Creation wrote What the Last Dawn of
Reckoning shall read. 中文

I propose to take the poet's description as my standard. Perhaps this may seem an odd choice; but there is no doubt that his words express what is in our minds when we refer to determinism. The other two definitions need to be scrutinised suspiciously; we are afraid there may be a catch in them. In saying that the physical universe as now pictured is not a universe in which “the first morning of creation wrote what the last dawn of reckoning shall read”, we make it clear that the abandonment of determinism is no technical quibble, but is to be understood in the most ordinary sense of the words. 中文

It is important to notice that all three definitions introduce the time-element. Determinism postulates not merely causes but pre-existing causes. Determinism means predetermination. Hence in any argument about determinism the dating of the alleged causes is an important matter; we must challenge them to produce their birth certificates.

中文

Ten years ago, practically every physicist of repute was, or believed himself to be, a determinist, at any rate so far as inorganic phenomena are concerned. He believed that he had come across a scheme of strictly causal law, and that it was the primary aim of science to fit as much of our experience as possible into such a scheme. The methods, definitions, and conceptions of physical science were so much bound up with this assumption of determinism that the limits (if any) of the scheme of causal law were looked upon as the ultimate limits of physical science. [中文](#)

To see the change that has occurred, we need only refer to a recent book which goes as deeply as anyone has yet penetrated into the fundamental structure of the physical universe, Dirac's "Quantum Mechanics". I do not know whether Dirac is a determinist or not; quite possibly he believes as firmly as ever in the existence of a scheme of strict causal law. But the significant thing is that in this book he has no occasion to refer to it. In the fullest account of what has yet been ascertained as to the way things work, causal law is not mentioned.

[中文](#)

This is a deliberate change in the aim of theoretical physics. If the older physicist had been asked why he thought that progress consisted in fitting more and more phenomena into a deterministic scheme, his most effective reply would have been "What else is there to do?" A book such as Dirac's supplies the answer. For the new aim has been extraordinarily fruitful, and phenomena which had hitherto baffled exact mathematical treatment are now calculated and the predictions are verified by experiment. We shall see presently that indeterministic law is as useful a basis for practical predictions as deterministic law was. By all practical tests, progress along this new branch track must be recognised as a great advance in knowledge. No doubt some will say "Yes, but it is often necessary to make a detour in order to get round an obstacle. Presently we shall have passed the obstacle and be

able to join the old road again.” I should say rather that we are like explorers on whom at last it has dawned that there are other enterprises worth pursuing besides finding the North-West Passage; and we need not take too seriously the prophecy of the old mariners who regard these enterprises as a temporary diversion to be followed by a return to the “true aim of geographical exploration”. But at the moment I am not concerned with prophecy and counter-prophecy; the important thing is to grasp the facts of the present situation. 中文

Secondary Law

Let us first try to see how the new aim of physical science originated. We observe certain regularities in the course of Nature and formulate these as “laws of Nature”. Laws may be stated positively or negatively, “Thou shalt” or “Thou shalt not”. For the present purpose it is most convenient to formulate them negatively. Consider the following two regularities which occur in our experience:

(a) We never come across equilateral triangles whose angles are unequal.

(b) We never come across 13 trumps in our hand at bridge. 中文

In our ordinary outlook we explain these regularities in fundamentally different ways. We say that the first occurs because the contrary experience is *impossible*; the second occurs because the contrary experience is *too improbable*. 中文

This distinction is entirely theoretical; there is nothing in the observations themselves to suggest to which type a particular regularity belongs. We recognise that “impossible” and “too improbable” can both give adequate explanation of any observed uniformity of experience, and the older theory rather haphazardly explained some uniformities one way and other uniformities the other way. In the new physics we make no such discrimination; the union

obviously must be on the basis of (b), not (a). It can scarcely be supposed that there is a law of Nature which makes the holding of 13 trumps in a properly dealt hand impossible; but it *can* be supposed that our failure to find equilateral triangles with unequal angles is only because such triangles are too improbable. 中文

We must, however, first consider the older view which distinguished type (a) as a special class of regularity. Accordingly, there were two types of natural law. The earth keeps revolving round the sun, because it is *impossible* it should run away. Heat flows from a hot body to a cold, because it is *too improbable* that it should flow the other way. I call the first type *primary* law, and the second type *secondary* law. The recognition of secondary law was the thin end of the wedge that ultimately cleft the deterministic scheme. 中文

For practical purposes primary and secondary law exert equally strict control. The improbability referred to in secondary law is so enormous that failure even in an isolated case is not to be seriously contemplated. You would be utterly astounded if heat flowed from you to the fire so that you got chilled by standing in front of it, although such an occurrence is judged by physical theory to be not impossible but improbable. Now it is axiomatic that in a deterministic scheme nothing is left to chance; a law which has the ghost of a chance of failure cannot form part of the scheme. So long as the aim of physics is to bring to light a deterministic scheme, the pursuit of secondary law is a blind alley since it leads only to probabilities. The determinist is not content with a law which prescribes that, given reasonable luck, the fire will warm me; he admits that that is the probable effect, but adds that somewhere at the base of physics there are other laws which prescribe just what the fire will do to me, luck or no luck. 中文

To borrow an analogy from genetics, determinism is a *dominant character*. We can (and indeed must) have secondary indeterministic

laws within any scheme of primary deterministic law—laws which tell us what is likely to happen but are overridden by the dominant laws which tell us what must happen. So determinism watched with equanimity the development of indeterministic law within itself. What matter? Deterministic law remains dominant. It was not foreseen that indeterministic law when fully grown might be able to stand by itself and supplant its dominant parent. There is a game called “Think of a number”. After doubling, adding, and other calculations, there comes the direction “Take away the number you first thought of”. We have reached that position in physics, and the time has come to take away the determinism we first thought of. [中文](#)

The growth of secondary law within the deterministic scheme was remarkable, and gradually sections of the subject formerly dealt with by primary law were transferred to it. There came a time when in some of the most progressive branches of physics secondary law was used exclusively. The physicist might continue to profess allegiance to primary law but he ceased to utilise it. Primary law was the gold to be kept stored in vaults; secondary law was the paper to be used for actual transactions. No one minded; it was taken for granted that the paper was backed by gold. At last came the crisis, and *physics went off the gold standard*. This happened very recently, and opinions are divided as to what the result will be. Prof. Einstein, I believe, fears disastrous inflation, and urges a return to sound currency—if we can discover it. But most theoretical physicists have begun to wonder why the now idle gold should have been credited with such magic properties. At any rate the thing has happened, and the immediate result has been a big advance in atomic physics. [中文](#)

We have seen that indeterministic or secondary law accounts for regularities of experience, so that it can be used for predicting the future as satisfactorily as primary law. The predictions and regularities refer to average behaviour of the vast number of particles concerned

in most of our observations. When we deal with fewer particles the indeterminacy begins to be appreciable, and prediction becomes more of a gamble; until finally the behaviour of a single atom or electron has a very large measure of indeterminacy. Although some courses may be more probable than others, backing an electron to do anything is in general as uncertain as backing a horse. [中文](#)

It is commonly objected that our uncertainty as to what the electron will do in the future is due not to indeterminism but to ignorance. It is asserted that some character exists in the electron or its surroundings which decides its future, only physicists have not yet learned how to detect it. You will see later how I deal with this suggestion. But I would here point out that if the physicist is to take any part in the wider discussion on determinism as affecting the significance of our lives and the responsibility of our decisions, he must do so on the basis of what he has discovered, not on the basis of what it is conjectured he might discover. His first step should be to make clear that he no longer holds the position, occupied for so long, of chief advocate for determinism, and that he is *unaware* of any deterministic law in the physical universe. He steps aside and leaves it to others—philosophers, psychologists, theologians—to come forward and show, if they can, that they have found indications of determinism in some other way.† If no one comes forward, the hypothesis of determinism presumably drops; and the question whether physics is actually antagonistic to it scarcely arises. It is no use looking for an opposer until there is a proposer in the field. [中文](#)

Inferential Knowledge

It is now necessary to examine rather closely the nature of our knowledge of the physical universe. [中文](#)

All our knowledge of physical objects is by inference. We have no means of getting into direct contact with them; but they emit and

scatter light waves, and they are the source of pressures transmitted through adjacent material. They are like broadcasting stations that send out signals which we can receive. At one stage of the transmission the signals pass along nerves within our bodies. Ultimately visual, tactual, and other sensations are provoked in the mind. It is from these remote effects that we have to argue back to the properties of the physical object at the far end of the chain of transmission. The image which arises in the mind is not the physical object, though it is a source of information about the physical object; to confuse the mental object with the physical object is to confuse the clue with the criminal. Life would be impossible if there were no kind of correspondence between the external world and the picture of it in our minds; and natural selection (reinforced where necessary by the selective activity of the Lunacy Commissioners) has seen to it that the correspondence is sufficient for practical needs. But we cannot rely on the correspondence, and in physics we do not accept any detail of the picture unless it is confirmed by more exact methods of inference.

中文

The external world of physics is thus a universe populated with *inferences*. The inferences differ in degree and not in kind. Familiar objects which I handle are just as much inferential as a remote star which I infer from a faint image on a photographic plate, or an “undiscovered” planet inferred from irregularities in the motion of Uranus. It is sometimes asserted that electrons are essentially more hypothetical than stars. There is no ground for such a distinction. By an instrument called a Geiger counter, electrons may be counted one by one as an observer counts one by one the stars in the sky. In each case the actual counting depends on a remote indication of the physical object. Erroneous properties may be attributed to the electron by fallacious or insufficiently grounded inference, so that we may have a totally wrong impression of what it is we are counting; but the same is equally true of the stars.

中文

In the universe of inferences, past, present, and future appear simultaneously, and it requires scientific analysis to sort them out. By a certain rule of inference, namely, the law of gravitation, we infer the present or past existence of a dark companion to a star; by an application of the same rule of inference we infer the existence on Aug. 11, 1999, of a configuration of the sun, earth, and moon, which corresponds to a total eclipse of the sun. The shadow of the moon on Cornwall in 1999 is already in the universe of inference. It will not change its status when the year 1999 arrives and the eclipse is observed; we shall merely substitute one method of inferring the shadow for another. The shadow will always be an inference. I am speaking of the object or condition in the external world which is called a shadow; our perception of darkness is not the physical shadow, but is one of the possible clues from which its existence can be inferred. [中文](#)

Of particular importance to the problem of determinism are our inferences about the past. Strictly speaking, our direct inferences from sight, sound, touch, all relate to a time slightly antecedent; but often the lag is more considerable. Suppose that we wish to discover the constitution of a certain salt. We put it in a test tube, apply certain reagents, and ultimately reach the conclusion that it *was* silver nitrate. It is no longer silver nitrate after our treatment of it. This is an example of retrospective inference: the property which we infer is not that of “being X” but of “having been X”. [中文](#)

We noted at the outset that in considering determinism the alleged causes must be challenged to produce their birth certificates so that we may know whether they really were pre-existing. Retrospective inference is particularly dangerous in this connexion because it involves antedating a certificate. The experiment above mentioned certifies the chemical constitution of a substance, but the date we write on the certificate is earlier than the date of the experiment. The

antedating is often quite legitimate; but that makes the practice all the more dangerous, it lulls us into a feeling of security. 中文

Retrospective Characters

To show how retrospective inference might be abused, suppose that there were no way of learning the chemical constitution of a substance without destroying it. By hypothesis a chemist would never know until after his experiment what substance he had been handling, so that the result of every experiment he performed would be entirely unforeseen. Must he then admit that the laws of chemistry are chaotic? A man of resource would override such a trifling obstacle. If he were discreet enough never to say beforehand what his experiment was going to demonstrate, he might give edifying lectures on the uniformity of Nature. He puts a lighted match in a cylinder of gas, and the gas burns. "There you see that hydrogen is inflammable." Or the match goes out. "That proves that nitrogen does not support combustion." Or it burns more brightly. "Evidently oxygen feeds combustion." "How do you know it was oxygen?" "By retrospective inference from the fact that the match burned more brightly." And so the experimenter passes from cylinder to cylinder; the match sometimes behaves one way and sometimes another, thereby beautifully demonstrating the uniformity of Nature and the determinism of chemical law! It would be unkind to ask how the match must behave in order to indicate indeterminism. 中文

If by retrospective inference we infer characters at an earlier date, and then say that those characters invariably produce at a future date the manifestation from which we inferred them, we are working in a circle. The connexion is not causation but definition, and we are not prophets but tautologists. We must not mix up the genuine achievements of scientific prediction with this kind of charlatanry, or the observed uniformities of Nature with those so easily invented by our imaginary lecturer. It is easily seen that to avoid vicious circles we

must abolish purely retrospective characteristics—those which are never found as existing but always as having existed. If they do not manifest themselves until the moment that they cease to exist, they can never be used for prediction except by those who prophesy after the event. 中文

Chemical constitution is not a retrospective character, though it is often inferred retrospectively. The fact that silver nitrate can be bought and sold shows that there is a property of *being* silver nitrate as well as of *having been* silver nitrate. Apart from special methods of determining the constitution or properties of a substance without destroying it, there is one general method widely applicable. We divide the specimen into two parts, analyse one part (destroying it if necessary), and show that its constitution *has been* X ; then it is usually a fair inference that the constitution of the other part is X . It is sometimes argued that in this way a character inferable retrospectively must always be also inferable contemporaneously; if that were true, it would remove all danger of using retrospective inference to invent fictitious characters as causes of the events observed. Actually the danger arises just at the point where the method of sampling breaks down, namely, when we are concerned with characteristics supposed to distinguish one individual atom from another atom of the same substance; for the individual atom cannot be divided into two samples, one to analyse and one to preserve. Let us take an example:

It is known that potassium consists of two kinds of atoms, one kind being radioactive and the other inert. Let us call the two kinds $K\alpha$ and $K\beta$. If we observe that a particular atom bursts in the radioactive manner, we shall infer that it was a $K\alpha$ atom. Can we say that the explosion was predetermined by the fact that it was a $K\alpha$ and not a $K\beta$ atom? On the information stated there is no justification at all; $K\alpha$ is merely an antedated label which we attach to the atom when we see

that it has burst. We can always do that, however undetermined the event may be which occasions the label. Actually, however, there is more information which shows that the burst is not undetermined. Potassium is found to consist of two isotopes of atomic weights 39 and 41; and it is believed that 41 is the radioactive kind, 39 being inert. It is possible to separate the two isotopes and to pick out atoms known to be K^{41} . Thus, K^{41} is a contemporaneous character, and can legitimately predetermine the subsequent radioactive outburst; it replaces $K\alpha$ which was a retrospective character. 中文

So much for the fact of outburst; now consider the time of outburst. Nothing is known as to the time when a particular K^{41} atom will burst except that it will probably be within the next thousand million years. If, however, we observe that it bursts at a time t , we can ascribe to the atom the retrospective character K^t , meaning that it had (all along) the property that it was going to burst at time t . Now, according to modern physics, the character K^t is not manifested in any way—is not even represented in our mathematical description of the atom—until the time t when the burst occurs and the character K^t , having finished its job, disappears. In these circumstances K^t is not a predetermining cause. Our retrospective labels and characters add nothing to the plain observational fact that the burst occurred without warning at the moment t ; they are merely devices for ringing a change on the tenses.

中文

The time of break-up of a radioactive atom is an example of extreme indeterminism; but it must be understood that, according to current theory, all future events are indeterminate in greater or lesser degree, and differ only in the margin of uncertainty. When the uncertainty is below our limits of measurement, the event is looked upon as practically determinate; determinacy in this sense is relative to the refinement of our measurements. A being accustomed to time on the cosmic scale, who was not particular to a few hundred million years

or so, might regard the time of break-up of the radioactive atom as practically determinate. There is one unified system of secondary law throughout physics and a continuous gradation from phenomena predictable with overwhelming probability to phenomena which are altogether indeterminate. [中文](#)

Criticism of Indeterminism

In saying that there is no contemporaneous characteristic of the radioactive atom determining the date at which it is going to break up, we mean that in the picture of the atom as drawn in present-day physics no such characteristic appears; the atom which will break up in 1960 and the atom which will break up in the year 150,000 are drawn precisely alike. But, it will be said, surely that only means that the characteristic is one which physics has not yet discovered; in due time it will be found and inserted in the picture either of the atom or its environment. If such indeterminacy were exceptional, that would be the natural conclusion, and we should have no objection to accepting such an explanation as a likely way out of a difficulty. But the radioactive atom was not brought forward as a difficulty; it was brought forward as a favourable illustration of that which applies in greater or lesser degree to all kinds of phenomena. There is a difference between explaining away an exception and explaining away a rule. [中文](#)

The persistent critic continues: "You are evading the point. I contend that there are characteristics unknown to you which completely predetermine not only the time of break-up of the radioactive atom but also all physical phenomena. How do you know there are not? You are not omniscient." [中文](#)

The curious thing is that the determinist who takes this line is under the illusion that he is adopting a more modest attitude in regard to our scientific knowledge than the indeterminist. The indeterminist is

accused of claiming omniscience. I will not make quite the same countercharge against the determinist; but surely it is only a man who thinks himself *nearly* omniscient who would have the audacity to start enumerating all the things which (it occurs to him) might exist without his knowing it. I am so far from omniscient that my list would contain innumerable entries. If it is any satisfaction to the critic, my list does include deterministic characters—along with Martian irrigation works, ectoplasm, etc.—as things which might exist unknown to me. 中文

It must be realised that determinism is a positive assertion about the behaviour of the universe. It is not sufficient for the determinist to claim that there is no fatal objection to his assertion; he must produce some reason for making it. I do not say he must prove it, for in science we are ready to believe things on evidence falling short of strict proof. If no reason for asserting it can be given, it collapses as an idle speculation. It is astonishing that even scientific writers on determinism advocate it without thinking it necessary to say anything in its favour, merely pointing out that the new physical theories do not actually disprove determinism. If that really represents the status of determinism, no reputable scientific journal would waste space over it. Conjectures put forward on slender evidence are the curse of science; a conjecture for which there is no evidence at all is an outrage. So far as the physical universe is concerned, determinism appears to explain nothing; for in the modern books which go farthest into the theory of the phenomena no use is made of it. 中文

Indeterminism is not a positive assertion. I am an indeterminist in the same way that I am an anti-moon-is-made-of-green-cheese-ist. That does not mean that I especially identify myself with the doctrine that the moon is not made of green cheese. Whether or not the green cheese lunar theory can be reconciled with modern astronomy is scarcely worth inquiring; the main point is that green-cheesism, like

determinism, is a conjecture that we have no reason for entertaining. Undisprovable hypotheses of that kind can be invented *ad lib*. [中文](#)

Principle of Uncertainty

The mathematical treatment of an indeterminate universe does not differ much in form from the older treatment designed for a determinate universe. The equations of wave mechanics used in the new theory are not different in principle from those of hydrodynamics. The fact is that, since an algebraic symbol can be used to represent either a known or an unknown quantity, we can symbolise a definitely predetermined future or an unknown future in the same way. The difference is that whereas in the older formulae every symbol was theoretically determinable by observation, in the present theory there occur symbols the values of which are not assignable by observation. [中文](#)

Hence, if we use the equations to predict, say, the future velocity of an electron, the result will be an expression containing, besides known symbols, a number of undeterminable symbols. The latter make the prediction indeterminate. (I am not here trying to prove or explain the indeterminacy of the future; I am only stating how we adapt our mathematical technique to deal with an indeterminate future.) The indeterminate symbols can often (or perhaps always) be expressed as unknown phase-angles. When a large number of phase-angles are involved, we may assume in averaging that they are uniformly distributed from 0° to 360° , and so obtain predictions which could only fail if there has been an unlikely coincidence of phase-angles. That is the secret of all our successful prophecies; the unknowns are not eliminated by determinate equations but by averaging. [中文](#)

There is a very remarkable relation between the determined and the undetermined symbols, which is known as Heisenberg's Principle of Uncertainty. The symbols are paired together, every determined

symbol having an undetermined symbol as partner. I think that this regularity makes it clear that the occurrence of undetermined symbols in the mathematical theory is not a blemish; it gives a special kind of symmetry to the whole picture. The theoretical limitation on our power of predicting the future is seen to be systematic, and it cannot be confused with other casual limitations due to our lack of skill.

中文

Let us consider an isolated system. It is part of a universe of inference, and all that can be embodied in it must be capable of being inferred from the influence which it broadcasts over its surroundings. Whenever we state the properties of a body in terms of physical quantities, we are imparting knowledge as to the response of various external indicators to its presence and nothing more. A knowledge of the response of all kinds of objects would determine completely its relation to its environment, leaving only its unget-at-able inner nature, which is outside the scope of physics. Thus, if the system is really isolated so that it has no interaction with its surroundings, it has no properties belonging to physics, but only an inner nature which is beyond physics. So we must modify the conditions a little. Let it for a moment have some interaction with the world exterior to it; the interaction starts a train of influences which may reach an observer; he can from this one signal draw an inference about the system, that is, fix the value of one of the symbols describing the system or fix one equation for determining their values. To determine more symbols there must be further interactions, one for each new value fixed. It might seem that in time we could fix all the symbols in this way, so that there would be no undetermined symbols in the description of the system. But it must be remembered that the interaction which disturbs the external world by a signal also reacts on the system. 中文

There is thus a double consequence; the interaction starts a signal through the external world informing us that the value of a certain

symbol p in the system is p_1 , and at the same time it alters to an indeterminable extent the value of another symbol q in the system. If we had learned from former signals that the value of q was q_1 , our knowledge will cease to apply, and we must start again to find the new value of q . Presently there may be another interaction which tells us that q is now q_2 ; but the same interaction knocks out the value p_1 and we no longer know p . It is of the utmost importance for prediction that a paired symbol and not the inferred symbol is upset by the interaction. If the signal taught us that at the moment of interaction p was p_1 , but that p had been upset by the interaction and the value no longer held good, we should never have anything but retrospective knowledge—like the chemistry lecturer to whom I referred above. Actually we can have contemporaneous knowledge of the values of half the symbols, but never more than half. We are like the comedian picking up parcels who, each time he picks up one, drops another.

中文

There are various possible transformations of the symbols and the condition can be expressed in another way. Instead of two paired symbols, one wholly known and the other wholly unknown, we can take two symbols each of which is known with some uncertainty; then the rule is that the product of the two uncertainties is fixed. Any interaction which reduces the uncertainty of determination of one increases the uncertainty of the other. For example, the position and velocity of an electron are paired in this way. We can fix the position with a probable error of 0.001 mm. and the velocity with a probable error of about 1 km. per sec.; or we can fix the position to 0.0001 mm. and the velocity to 10 km. per sec.; and so on. We divide the uncertainty how we like, but we cannot get rid of it. If current theory is right, this is not a question of lack of skill or a perverse delight of Nature in tantalising us; for the uncertainty is actually embodied in the theoretical picture of the electron; so that if we describe something as having exact position and velocity we cannot be

describing an electron. 中文

If we divide the uncertainty in position and velocity at time t_1 in the most favourable way, we find that the predicted position of the electron one second later (at time t_2) is uncertain to about five centimetres. That represents the extent to which the future position is not predetermined by anything existing one second earlier. If the position at time t_2 always remained uncertain to this extent, there would be no failure of determinism, for the thing we had failed to predict (exact position at time t_2) would be meaningless. But *when the second has elapsed* we can measure the position of the electron to 0.001 mm. or even more closely, as already stated. This accurate position is not predetermined; we have to wait until the time arrives and then measure it. It may be recalled that the new knowledge is acquired at a price. Along with our rough knowledge of position (to 5 cm.) we had a fair knowledge of the velocity; but when we acquire more accurate knowledge of the position, the velocity goes back into extreme uncertainty. 中文

We might spend a long while admiring the detailed working of this cunning arrangement by which we are prevented from finding out more than we ought to know. But I do not think we should look on these as Nature's devices to prevent us from seeing too far into the future. They are the devices of the mathematician who has to protect himself from making impossible predictions. It commonly happens that when we ask silly questions, mathematical theory does not directly refuse to answer but gives a non-committal answer like $\frac{0}{0}$, out of which we cannot wring any definite meaning. Similarly, when we ask where the electron will be tomorrow, mathematical theory does not give the straightforward answer, "It is impossible to say, because it is not yet decided", because that is beyond the resources of an algebraic vocabulary. It gives us an ordinary formula of x 's and y 's, but makes sure that we cannot possibly find out what the formula means

—until tomorrow.

[中文](#)

Mental Indeterminism

I have, perhaps fortunately, left myself no time to discuss the effect of indeterminacy in the physical universe on our general outlook. I will content myself with stating in summary form the points which seem to arise. [中文](#)

(1) If the whole physical universe is deterministic, mental decisions (or at least *effective* mental decisions) must also be predetermined. For if it is predetermined in the physical world (to which your body belongs) that there will be a pipe between your lips on Jan. 1, the result of your mental struggle on Dec. 31 as to whether you will give up smoking in the New Year is evidently predetermined. The new physics thus opens the door to indeterminacy of mental phenomena, whereas the old deterministic physics bolted and barred it completely.

[中文](#)

(2) The door is opened slightly, but apparently the opening is not wide enough; for according to analogy with inorganic physical systems, we should expect the indeterminacy of human movements to be quantitatively insignificant. In some way we must transfer to human movements the wide indeterminacy characteristic of atoms, instead of the almost negligible indeterminacy manifested by inorganic systems of comparable scale. I think this difficulty is not insuperable, but it must not be underrated. [中文](#)

(3) Although we may be uncertain as to the intermediate steps, we can scarcely doubt what is the final answer. If the atom has indeterminacy, surely the human mind will have an equal indeterminacy; for we can scarcely accept a theory which makes out the mind to be more mechanistic than the atom. [中文](#)

(4) Is the human will really more free if its decisions are swayed by

new factors born from moment to moment than if they are the outcome solely of heredity, training, and other predetermining causes? On such questions as these we have nothing new to say. Argument will no doubt continue “about it and about”. But it seems to me that there is a far more important aspect of indeterminacy. It makes it possible that the mind is not utterly deceived as to the mode in which its decisions are reached. On the deterministic theory of the physical world, my hand in writing this address is guided in a predetermined course according to the equations of mathematical physics; my mind is unessential—a busybody who invents an irrelevant story about a scientific argument as an explanation of what my hand is doing—an explanation which can only be described as a downright lie. If it is true that the mind is so utterly deceived in the story it weaves round our human actions, I do not see where we are to obtain our confidence in the story it tells of the physical universe. 中文

Physics is becoming difficult to understand. First relativity theory, then quantum theory, then wave mechanics have transformed the universe, making it seem ever more fantastic to our minds. Perhaps the end is not yet. But there is another side to this transformation. Naïve realism, materialism, the mechanistic hypothesis were simple; but I think that it was only by closing our eyes to the essential nature of experience, relating as it does to the reactions of a conscious being, that they could be made to seem credible. These revolutions of scientific thought are clearing up the deeper contradictions between life and theoretical knowledge, and the latest phase with its release from determinism marks a great step onwards. I will even venture to say that in the present theory of the physical universe we have at last reached something which a reasonable man might almost believe.

中文

(129, 233-240; 1932)

† With the view of learning what might be said from the philosophical side against the abandonment of determinism, I took part in a symposium of the Aristotelian Society and Mind Association in July 1931. Indeterminists were strongly represented, but unfortunately there were no determinists in the symposium, and apparently none in the audience which discussed it. I can scarcely suppose that determinist philosophers are extinct, but it may be left to their colleagues to deal with them.

决定论的衰落*

阿瑟·爱丁顿

10年前，阿瑟·爱丁顿在《自然》杂志上发表文章声称实际上所有的知名物理学家都是决定论者，至少他们面对物理过程时都是如此。物理学家们认为他们拥有一个因果相连的庞大科学体系——最明显的例子是经典力学领域，并且人们还在利用这种模式解释更多的现象。但现在量子理论改变了所有的一切，人们对此的反应各不相同：有人将信将疑，有人冷嘲热讽，还有些人漠不关心。然而，爱丁顿指出：不能认为新出现的非决定论是一种反科学的方法。他把旧有的决定论或称“基本定律”比作科学上的金本位，现在被“第二代”货币所取代。现在，大多数物理学家都不能理解为什么这些基本定律曾经受到过如此的推崇。 [英文](#)

在理论物理领域里，决定论的身影渐渐淡去。人们对它的退出持有各种不同的观点。有些作者对此表示怀疑，不相信决定论真的被排除了；有些则认为它仅仅是物理学领域内部的变化，对一般的哲学思想没有任何影响；另一些人认为这是对奇怪现象的合理性解释；还有一部分人冷眼旁观，等着看决定论是否会卷土重来。 [英文](#)

摒弃决定论绝不是要放弃科学方法；在对观测到的现象进行数学分析时，它也的确提高了分析的能力和精度。从另一方面来说，我无法认同那些低估了这个变化所具有的一般哲学意义的人。我们不能轻描淡写地摆脱两百多年来被自然科学所一致采取的看法；并且这使得我们必须重新审视一个有关存在物的复杂问题。在这里，我将主要就物质世界进行探讨，而几乎不涉及思想决定论和自由意志。最好把它们留给那些更加善于探讨此类问题的人，只要他们能意识到目前在物理学方面已经出现的新情况。而我目前几乎看不出任何意识到这种情况的迹象。 [英](#)

决定论的定义

让我们首先确保我们对决定论的含义有一致的认识。我要引用三种定义或描述给你们作参考。第一种是一位数学家（拉普拉斯）的叙述：

我们应把目前宇宙的状态看作是它先前状态的结果和未来状态的原因。假定有这么一位天才，他在某个确定的瞬间知道了所有驱动自然界运转的力以及组成宇宙的所有实体的几个位置，如果他还具有足够的才智来收集分析这些数据的话，他就能把从最大物体到最小原子的运动都包括在同一个公式中。对他来说，没有什么是不确定的，过去和未来全在他的掌握之中。人类的完美主义思想为天文学描绘了一个如此聪慧的人的大致轮廓。……对我们刚才幻想中的这位天才而言，他为探寻到真理所做的努力几乎是不受限制的。 [英文](#)

第二种定义来自于一位哲学家（布罗德）的观点：

“决定论”指的是下述学说：设 S 为任意一个物质， ψ 为任意一种特性， t 为任意一个时刻。假设 t 时刻特性为 ψ 的物质 S 实际上处于状态 δ ，那么认为：世界上的任意其他物质都处于实际状态，并且物质 S 本来应该处于关于特性 ψ 的其他两种状态中的一种的复合推断是不可能成立的。[这三种状态（ δ 是其中一种）分别为：具备特性 ψ 、不具备特性 ψ 和正在变化的状态。] [英文](#)

第三种说法则是一位诗人（奥马尔·海亚姆）提出来的：

最初的泥丸捏成了最终的人形，

最后的收成便是那最初的种子：

天地开辟时的老文章写就了天地掩闭时的字句。 [英文](#)

我选择诗人的描述作为我对决定论的理解标准。看起来这可能是个奇怪的选择，但是毫无疑问他的描述正是我们提到决定论时脑海里所浮现的想法。其他的两个定义则需以怀疑的态度仔细研究，恐怕它们之中会存在某些陷阱。当我们提到现在所描绘的物质世界时，指的并不是那

种“天地开辟时的老文章写就了天地掩闭时的字句”的宇宙。我们要让人明白放弃决定论并不是一种巧妙的推托，而是用一种最平实的语言就可以理解的。 [英文](#)

值得特别注意的是三种定义都引入了时间元素。决定论不仅仅是要假定存在的起因，而是要假定起因在早先就已经存在了。决定论意味着预先决定。因此在任何有关决定论的争论中，确定所谓起因的时间是一个非常重要的问题，我们必须让它们为自身的起源提供证明。 [英文](#)

十年前，至少是在考虑无机系统的物理现象时，几乎所有知名的物理学家都是，或者认为他们自己是，一个决定论者。他们确信自己已经发现了一个严格的因果律体系，并且相信科学的首要目的就是尽可能地把我们的日常体验纳入到这个体系内。物理科学中的方法、定义以及概念受到这种决定论假设过多的限制，以至于人们把因果律体系的局限性（如果有的话）看作是物理科学的极限。 [英文](#)

要了解已经出现的改变，我们仅仅需要参考最近出版的一本书——狄拉克所著的《量子力学》，它比任何人都更深层次地触及到物质世界的基本结构。我不知道狄拉克是否是一个决定论者，他很有可能一直都坚信存在着严格的因果律体系。但是值得注意的是，在这本书里他没有提及这个问题。在对已经可以确定的事物运行规律的最全面的叙述中，并没有提到因果律。 [英文](#)

理论物理研究目标中的这样一个改变是经过深思熟虑的。如果年长些的物理学家被问及为什么科学的发展就在于把越来越多的现象纳入决定论的体系，那么他最有力的回应便是：“除此之外还有什么别的办法吗？”狄拉克所写的那样一本书给出了答案。因为新的研究目标已经产生了非凡的效果，迄今仍难以给出精确数学处理的物理现象现在也可以计算出来了，并且很多预言得到了实验的验证。现在我们应该明白，非决定论的规律和决定论的规律一样有效，都可以作为实际预测的原则。所有实践都证明，我们必须把在这个新分支方向上取得的进展看作是知识的巨大进步。毫无疑问，有些人会说：“对，但为了避开障碍物，通常会绕道而行。目前我们已经越过了障碍，可以重新回到以前的老路上去了。”不过我却这样认为：我们就像那些探险家，他们最后终于意识到，

除了去探寻西北通道以外，还有其他值得追求的事业。我们不需要过分看重老水手的预言，他们把这些事业当作是一种暂时性的消遣，随后还是要回到“地理大发现这个终极目标上”。但此刻我不关心那些预言和反预言的论调，重要的是把握目前的实际情况。 英文

次级定律

首先，让我们了解一下物理科学中的新目标是怎样出现的。我们观察自然过程中的某些规律，然后把它们明确表达为“自然定律”。这些定律既可以用肯定句式陈述也可以用否定句式陈述，比如“你应该”或者“你不应该”。对于当前的需要，用否定句式来阐明最为方便。在我们的生活经历中会出现以上两种规律：

(a) 我们绝不会见到一个等边三角形具有不相等的角。

(b) 在打桥牌时我们绝不会碰到手中有13张王牌的情况。 英文

文

按照我们通常的观点，我们可以用根本不同的方法来解释这些规则。我们会说出现第一种情况是因为不可能发生相反的情况；出现第二种情况是因为相反情况发生的概率极小。 英文

这完全是理论上的区分。观测本身不能说明某个特定的规律属于哪种类型。我们认为“不可能”和“概率极小”都可以对在实践中观测到的一致性做出合理的解释，早期的理论非常随意地对某些一致性以两种方式做出解释，而对其他的一致性又以另一种方式做出解释。在新物理学中，我们不作这样的区分；显然地，统一应基于标准(b)，而不是(a)。我们无法假设存在一种使手中有13张王牌的情况不可能发生的自然规律，但可以认为找不到不等角的等边三角形是因为这样的三角形出现的概率极小。 英文

然而，我们必须首先顾及过去的观点，即是把(a)区分出来作为一种特殊规律。因此，我们有了两类自然定律。地球持续围绕太阳运行是因为它不可能逃离开。热量从高温物体流向低温物体，是因为它流向相反方向的概率极小。我把第一种类型叫做基本定律，而把第二种叫做

次级定律。对次级定律的认识有如楔子的尖端终于劈开了决定论的框架。 [英文](#)

对于实际的目的来说，基本定律和次级定律发挥了同样严格的控制作用。在次级定律中提到的不可能性发生的概率非常大，即使出现了个别反例，也不会得到认真对待。如果热量从你身体上流向了火，你会十分惊讶，因为这样一来你站在火前就会感到寒冷刺骨，尽管在物理理论中这种情况并非不可能发生，而不过是发生的概率极小罢了。在决定论体系中，显然任何事情都不是偶然发生的；该体系中的所有定律都不可能出现任何反例。只要物理学的目标是要建立一个决定论的体系，那么我们对次级定律的研究只能走进死胡同，因为这样的研究只会得到有可能发生的结果。决定论者不会认可这样的规则：只要运气还可以我就能感到火的温暖。他承认这是一种可能出现的结果，可是他还会补充道，其物理基础应该以另一条定律来规定，即无论有没有运气，火都会使我温暖。 [英文](#)

借用一个遗传学的相似概念，决定论可以被看作是一种显性性状。我们能够（事实上是必须）把次级的非决定论置于任何一个基本的决定论体系之中，非决定论会告诉我们某件事情很有可能发生，然而那些告诉我们某件事情肯定会发生的显性定律优先于非决定论的定律。因此，决定论对其内部的非决定论定律的发展泰然视之。有什么关系呢？决定论的定律仍然是占优势地位的。没有人能预料见到当非决定论定律发展成熟后会独树一帜，取代占主导地位的母体。有一个游戏，名字叫做“猜数字”。在经过各种加倍、相加和其他运算后，最终达到“去掉最初所想的数字”的目的。在物理学中，我们已经实现了这样的目标，现在到了把我们最初想到的决定论去掉的时候了。 [英文](#)

在决定论体系中，次级定律的发展是引人注目的，一部分原本利用基本定律来处理的问题逐渐开始偏向使用次级定律。有一段时间，物理学中的一些最前沿的分支只采用次级定律进行研究。可能会有这样的情况，物理学家在继续宣称自己忠实于基本定律的同时已经不再使用它了。基本定律有如存放在金库中的黄金，而次级定律则是真正用于交易的纸币。没有人会介意，大家都认为纸币以黄金为基础是理所当然的事情。最终危机出现了，物理学放弃了金本位制。这是最近才发生的，并

且对结果将怎样人们说法不一。我确信，爱因斯坦教授对这种损失惨重的通货膨胀感到担忧，他强烈要求回归到健全的货币体系——当然，要以我们能找到这种货币体系为前提。不过大部分理论物理学家都已经开始质疑为什么应该认为现在闲置着的金子具有如此神奇的特性。无论如何，事情已经发生了，其直接的结果是使原子物理学取得了一个极大的进步。 [英文](#)

我们已经知道，非决定论定律，或者说次级定律，解释了由经验总结的规律，因此它同样可以像基本定律一样很好地预测未来。这些预测和规律与我们在大多数情况下观测到的大量粒子的平均状态相关。当我们处理数目较少的粒子时，不确定性开始变得明显起来，而预测更像是在冒险。直到最后，单个原子或电子的行为在很大程度上是不确定的。虽然有些过程比另一些过程更有可能发生，但是在通常情况下，预测一个电子将会怎样就如同预测一匹马一样难以确定。 [英文](#)

人们通常会对上述观点表示反对：我们不能确定电子将会如何运动的原因不是因为非决定论而是因为无知。有人声称，在电子内部或者它的周围环境中存在着确定其未来的某些特征因素，只是物理学家还不懂得如何才能检测到它。稍后你们就会知道我是如何看待这个观点的。但是这里我要指出，如果一个物理学家要在更广泛的意义上探讨决定论对我们的生活水平以及决策可靠性的影响，他就必须以他已经发现的物理现象为论据，而不能基于他推测出的可能会发现的现象。首先他应该搞清楚的是，他已经不再拥有占据了很久的决定论主要支持者的地位，并且他对物质世界中的任何决定论定律都毫无所知。他将退到一边，让其他人——哲学家、心理学家、神学家站出来说明他们以其他方式发现了决定论的迹象[†]，如果他们能找到的话。如果没有人挺身而出，那么决定论这个假设也许会被丢弃，也就不会引出物理学是否真的与决定论相抵触的问题。寻找反对者的努力都是徒劳的，除非有人自告奋勇。 [英文](#)

推理性的认识

现在有必要进一步审视我们对于物质世界的认识的本质。 [英文](#)

我们对物理对象的所有认识都是通过推理获得的。我们没有办法与它们直接接触，但是它们发射或散射光波，并把压力传递给相邻的物质。它们就像广播电台一样发射我们可以接收到的信号。在传输的一个阶段信号沿着我们身体里的神经传递，最终在我们的头脑里形成视觉、触觉以及其他感觉。通过这些远程效应，我们必须反过来辨明在传输链的另一端的物质的性质。我们头脑中产生的图像并不是物质本身，尽管它是与物质相关的信息的来源；把头脑中的物质图像混同为物质的实体就等于把线索混同于罪犯。如果不存在外部世界与它在我们头脑中形成的图像之间的对应，就不可能有我们的生活。在日常生活中，自然选择（必要时需要补充精神病委员的鉴定结果）所得到的对应似乎就已经足够满足实际需要了。但是我们不能依赖这些对应，在物理领域内，我们不能接受根据图像得到的任何信息，除非经过更为精确的推理方法的确证。

英文

物理学的外部世界就是这样一个充满推理的世界。这些推理只有程度上的差别，而没有本质上的区分。我手中的常见物体，与从照相底片上的模糊图像推断出的一颗遥远恒星，或从天王星运动的不规则性推出的“未知”行星一样，都可以由推论得到。有时候我们认为电子的不确定性高于恒星。但其实它们根本没有什么区别。利用一台名为盖革计数器的仪器，我们可以逐个将电子计数，犹如我们对天上的星星逐个计数一样。在上述两种情况下，计数实际上都取决于物质的远程影像。当然，对于电子错误的或根据不充分的推断会得到不正确的性质，所以对于我们所计量的对象，我们有可能得到一个完全错误的概念；然而我们在计数星星时，也同样会存在这样的情况。

英文

在这个充满推理的宇宙里，过去、现在和未来似乎是同时存在的，我们需要用科学分析法去区分。利用特定的推理规律，即引力定律，我们可以推断出某个恒星周边在现在或过去存在一个不发光的伴星；利用这个定律我们同样可以推断，在1999年8月11日，由于太阳、地球和月亮的相对位置会出现一次日全食。1999年将要在康沃尔出现的月亮阴影已经被推算了出来。这个推算在1999年到来和日食被观测到之前是不会改变的，我们只会不断替换推断出阴影的方法。阴影将永远是一个推断。我所说的阴影是外部世界中的物体或条件；其实我们对黑暗的感知

并不是物理上的阴影，而是可以从黑暗的存在推断出来的其中一种可能的线索。 [英文](#)

在决定论问题中最重要的一点是我们对于过去的推断。严格说来，我们通过视觉、听觉、触觉直接得来的推断在时间上都有很短的滞后；但这种滞后往往是比较重要的。假如我们想知道某种盐类的构成，我们会把它放入试管内，然后加入特定的试剂，最后得到结论，原来它是硝酸银。在我们对它做了处理之后它已经不再是硝酸银了。这就是一个回顾性推理的例子：我们推出的结论不是“是X”，而是“曾经是X”。 [英文](#)

我们从一开始注意到，在讨论决定论的时候，那些所谓的原因必须提供自己的出生证明，这样我们才能够知道它们是否的确是早已存在的。就此而论，回顾性推理是非常不可靠的，因为它需要提前提供证明。上面提到的实验证明了物质的化学成分，然而鉴定书上所证实的物质的存在日期要先于实验的日期。这种提前通常是非常合理的，但在实际操作中更加危险，因为它让我们产生了一种虚假的安全感。 [英文](#)

回顾性的特征

为了表明回顾性的推理是如何被滥用的，假定如果不破坏物质就没有任何办法获知它的化学成分。根据这个假设，一个化学家在他进行实验前不会知道他所要测试的物质的化学成分，于是他所做的所有实验的结果都是不可预见的。那么他是否必须承认，所有的化学规律都是杂乱无章的？聪明人知道要先忽略掉这些不重要的障碍。如果他足够谨慎，从不在实验前说出自己的实验要去证明什么，那么他也许会对自然齐一性问题发表富有启发性的演讲。他把一根燃烧的火柴扔进一瓶气体中，气体燃烧起来。然后他说，“你们看，氢气是易燃的”。或者是火柴熄灭了。“这证明氮气是不能助燃的”。或者是火柴燃烧得更剧烈了。“很明显氧气是助燃的”。“你怎么知道它就是氧气呢？”“这是从火柴燃烧得更加剧烈的事实中推断出来的。”然后实验者就这样一瓶又一瓶地进行试验；火柴有时呈现出这样一种状态，有时是另一种状态，从而完美地证实了自然齐一性以及化学规律的决定论！要是提问说火柴应该怎样表现才能够表明非决定论，那将是一个很不客气的问题。 [英文](#)

如果按照回顾性的推理，我们推断出的是较早以前的性质，然后说这些特性在以后会恒定不变地产生一种现象，而这种现象就是最初我们用来推断其性质的现象，我们就是在循环论证。这种关系并不是因果关系，而完全是在下定义。而我们也不是预言家，只是重复在使用同义词的人。我们决不能把真正的科学预言与此类骗术混同，也决不能把观察到的自然规律的一致性同那个虚构的演说家轻易编造出来的东西混同。很容易发现要避免这种恶性循环，我们就必须废除纯粹的回顾性特性——那些特性永远不是现有状态的特性，而总是曾经存在的某种状态的特性。如果这些性质在消逝的那一刻前不能表现出来，那么它们永远都不能用于预测，除非是在事后去做预测。 [英文](#)

化学组分并不具有回顾性的特性，尽管它总是在事后才被推断出来。硝酸银是可以被买卖的，这说明有这样一种表明它现在是硝酸银，而且它曾经是硝酸银的性质。除了一些特殊的方法可以测定物质的组成或性质而不用破坏它以外，还有一种得到广泛应用的一般方法。我们把这个样品分成两份，分析其中的一份（必要时可以去破坏它），并且表明它的成分曾经是 X ；然后通常可以合理地推出，另一份的成分就是 X 。于是时常有人认为，按照这种方式，一个可以在事后做回顾性推断得到的性质也可以实时推断出来；如果这是正确的话，那么就可以避开将回顾性推断得到的假想特性作为观测事件的原因所产生的全部危险。事实上，危险恰恰是在取样方法不再适用的情况下出现的，也就是当我们讨论能将同一个物质中单独的一个原子和另一个原子区分开的性质的时候。因为一个原子不能被分为两份，一份用于分析，另一份保留。让我们来看下面的例子：

我们知道，钾由两种类型的原子构成，一种是有放射性的，而另一种则是惰性的。我们把它们叫做 $K\alpha$ 和 $K\beta$ 。如果我们观察到一个原子以放射性的方式爆发，那么我们就推断它是 $K\alpha$ 原子。我们是否可以根据爆发原子是 $K\alpha$ 而不是 $K\beta$ 预先断定爆炸的发生？这里提供的信息表明，根本就没有这样的道理； $K\alpha$ 只是事先准备的一个标签，如果我们看见原子爆炸了就把这个标签贴在它上面。我们可以一直这样做下去，不管那个需要用到这个标签的事件是不是待定的。然而实际上，更多的信息表明爆发并不是未确定的。我们知道钾是由原子量分别为39和41的两种同位素组

成的；而且我们确信原子量是41的那种具有放射性，而39的那种则是惰性的。于是可以将这两种同位素区分开，挑选出被称为 K^{41} 的原子。这样 K^{41} 就是一个实时性质，能用来合理地预测它后续的放射性爆发；因而可以用它来代替 $K\alpha$ 这个回顾性的特性。 [英文](#)

对于爆发的现象就讨论到这里，现在我们要考虑爆发的时间。我们根本不知道一个 K^{41} 原子会在何时爆发，除非说它或许在今后的十亿年内会爆发。然而如果我们在时刻 t 观察到了它的爆炸，那么我们就可以认为这是由于此原子具有回顾性特性 K^t 造成的，这就表明它（自始至终）具有在时刻 t 爆发的性质。现在，根据现代物理学，这个性质 K^t 没有以任何一种方式得到证明——甚至不能用我们对原子的数学描述来表示——直到 t 时刻那个原子爆发，这个性质 K^t 在完成了自己的使命后销声匿迹了。在这种情况下 K^t 并不是一个可预测的起因。我们的回顾性的标签及特性没有给这个简单的实测现象增加任何内容，爆发毫无征兆地在时刻 t 发生了；这些标签和特性只不过是变化发生时的报警装置。 [英文](#)

放射性原子的衰变时刻就是一个极端的非决定论的例子；但是我们必须要明白，根据当前流行的理论，未来的事件，都或多或少是不可确定的，只是不确定度有所差别。如果这种不确定度在测量允许的范围以内，那么这件事情就可以被看作是可以确定的；在这种意义上确定性与我们的测量精度有关。一个习惯了以宇宙尺度度量时间的人，不会觉得几亿年上下的时间有什么特别了不起，那么他也许会认为放射性原子的衰变时间其实还是非常确定的。贯穿物理学的次级定律与从有绝对把握可以预测的现象到完全不能预测的现象之间的连续渐进是一个统一的体系。 [英文](#)

对非决定论的批评

当谈及没有一个实时性质可以确定放射性原子将要爆发的时间时，我们的意思是在当前物理学所描述的原子图像中不存在这种性质；对一个将要在1960年爆发的原子和一个将要在150,000年爆发的原子的描述是完全相同的。但是有人会说，那只能说明当前物理学还没有发现这种性质，在适当的时候我们总会发现这个性质，并把它添加到原子或其周围结构的理论中去。如果这种不确定性是例外情况，那么就会很自然地

得到上述结论，并且这种解释完全可以被我们拿来作为摆脱困难的可靠方法。但是放射性原子并不是作为一个难点提出的，提出它是为了在一定程度上能恰当地解释所有现象。对一个例外情况做出清楚的解释和一个规则做出清楚的解释是不一样的。 [英文](#)

但是固执的批评家还在继续：“你在回避要点。我认为有一些你所不知道的性质的不但能够完全预先确定放射性原子爆发的时间，还能够完全预先确定一切物理现象。你怎么知道没有那些性质呢？你又不是无所不知的。” [英文](#)

奇怪的是，持这种说法的决定论者错误地认为他们对待科学知识的态度比非决定论者更为谦虚。非决定论者因声称无所不知而受到指责。我并不打算采用完全一样的方式反击决定论者；但是可以肯定，只有自认为接近无所不知的人，才有胆量列举出所有（他想到的）可能存在但他自己不了解的东西。我远没有无所不知到可以列出无穷多条目的地步。如果能让那些批评家稍微满意一点的话，我承认我的列表中确实包括了一些确定性的特征，和火星灌溉工程、外质等一样，这些事物可能存在但非我所知。 [英文](#)

必须认识到，决定论是关于宇宙性质的一个积极的论断。但是这并不足以让决定论者断言，他的论断没有致命的缺陷；他必须提出一些理由令它成立。我并不是说他必须去证明它，因为在科学上，我们宁愿去相信一些证据明显却缺乏严格证明的事情。如果无法给出其成立的理由，那么它就会成为一个空洞的想法。让人惊讶的是，即使是那些就决定论问题运用科学方法讨论的作者也认为要支持它并不必去提它的优越性，只需说明新的物理理论与决定论并不抵触就可以了。如果该理论代表了决定论的观点，那么任何著名的科学杂志都不会为此浪费空间了。在缺乏足够证据的情况下妄加推测是科学的祸根，而在没有任何证据的时候就下结论则是一种暴行。就整个物理世界而言，决定论似乎没有解释任何事情；因为在深入探讨现象背后的理论的现代书籍中，没有用到决定论的观点。 [英文](#)

非决定论并不是一个积极的论断。我是一个非决定论者，同样也是一个反对月亮是由绿奶酪做成的人。这并不是说我想要特别强调自己赞

同月亮不是由绿奶酪做成的学说。至于月亮是由绿奶酪做成的理论是否能被当代天文学所接受，完全不值得去调查；关键点在于绿奶酪论就像决定论，是一个我们没有理由考虑的假设。我们可以随意创造这种无需证伪的猜想。 [英文](#)

不确定性原理

对一个不确定性宇宙的数学处理和以往对一个确定性宇宙所做的处理在形式上并没有太大区别。在这个新理论中，所用的波动力学方程跟流体力学方程没有原则上的差别。事实上，既然代数符号既可以用来代表一个已知的量也可以用来代表未知量，我们就可以用同样的方式来标识一个预先完全确定的未来或者一个不可确定的未来。不同之处是：按照以往的方式，在理论上每一个符号都是由观测确定的；而在当前的理论中，会有一些符号所代表的值不能通过观测给定。 [英文](#)

于是，如果说我们要用方程预测一个电子未来的速度，那么我们最后的表达式除了包括已知的符号外，还包括一些不可确定的符号。后者使得预测变得不可确定。（这里我并不是想证明或者解释未来的不可确定性；我只是在表述如何使用我们的数学技巧去处理不可确定的未来。）那些不可确定的符号常常（或可能总是）被表示成未知的相角。当涉及很多相角的时候，我们可以假设从平均意义上说它们从 0° 到 360° 是均匀分布的，所得预测只有在相角不太可能同时出现的情况下才会出现错误。这就是我们能够成功预言的秘密所在；不是通过确定的方程，而是通过取平均的方法来消除那些未确定的量。 [英文](#)

在确定的符号和不确定的符号之间有一个非常值得注意的关系，那就是海森堡测不准原理。这些符号都是成对的，每个确定的符号都对应着一个不确定的符号。我想这种规律性也清楚地告诉我们，在数学理论中出现不确定的符号并不是缺陷；它为整个物理图像带来了一种特殊的对称性。这个原理认为我们在预测未来能力上所能达到的极限取决于系统上的原因，而这种限制不会与因缺乏技巧而导致的偶然性限制混为一谈。 [英文](#)

让我们来考虑一个孤立的系统。那是可推理的宇宙的一部分，宇宙

中出现的一切事物都必须能够从其对周围环境所施加的影响中推断出来。每当我们用物理量描述一个物体的性质时，我们正在传递的信息只不过是使用不同外部指示物的响应来判断它的存在。如果知道了各类物体的响应，我们就可以完全确定它与周围环境的联系，而仅剩下它的“不能得到的”内部性质，那就是物理范畴以外的东西了。因此，如果一个系统是完全孤立的，那么它就不会与其周围的环境产生相互作用，因而不具备任何物理性质，而只具有超出物理范畴的内部性质。因此，我们必须把条件稍微修改一下。让它在一个短暂的时间内与外部世界产生一定的相互作用，这种作用引发一连串影响并被一个观测者所感知。观测者可以通过这个信号对上述系统进行推测，换言之，确定用来表述这个系统的某个符号的值，或者确定一个方程以便判定这些符号的值。要确定更多的符号，就必须有更进一步的相互作用，每一次相互作用都可以确定一个新符号的值。看起来通过这种方法我们总有一天会确定所有的符号，于是在描述这个系统的符号中就没有哪个是未确定的了。但是，一定要记住的是，这种通过信号对外部世界产生干扰的相互作用，同样也会对这个系统产生反作用。 [英文](#)

于是，这里就会存在两个结论：这个在外部世界产生了一个信号的相互作用告诉我们，某个符号 p 在系统中的值是 p_1 ，同时它还把系统中另一个符号 q 值的大小改变到一个不确定的值。如果我们已经从以前的信号得知 q 的值是 q_1 ，那么我们的这个认识将不再适用，我们必须重新开始寻找符号 q 的新值。不久可能有另一个相互作用告诉我们，现在的 q 值是 q_2 ，但同时这个相互作用又改变了 p_1 的值，于是我们不再确知 p 了。预测中至关重要的问题就是：相互作用会扰动成对出现的符号，而不是那个要推断的符号。如果某个信号告诉我们：在当前的相互作用中 p 为 p_1 ，但那个 p 已经被相互作用所扰动，它的值不再准确，除了对先前的回顾性认识外我们绝不会得到任何东西，就和我前面提到的那个化学老师一样。事实上我们可以同时知道一半符号的值，但不会超过一半。我们就像拣包裹的喜剧演员，每拣起一个就会又丢掉一个。 [英文](#)

这些符号可以有各种不同的变换，而条件也可以用另一种方式来表达。不采用这种其中一个完全确定而另一个完全不确定的成对符号，我们可以选取两个符号，其中每一个都带有一定的不确定性。于是就有了

这样一个定律：两个不确定度的乘积是确定的。任何降低其中一个不确定度的相互作用都会增加另一个的不确定度。例如，一个电子的位置和速度以这种方式成对的。我们可以把位置的概率误差定为 0.001 mm ，因而速度的概率误差大约是 1 km/s ；或者我们可以把位置的概率误差定为 0.0001 mm ，因而速度的概率误差是 10 km/s ，依此类推。我们可以按照我们的喜好来分配这个不确定度，但却不能摆脱它。如果目前的理论是正确的，那么就不存在缺乏技巧或大自然偏偏要与我们作对的问题；这是因为这种不确定性实实在在地蕴涵在电子的理论图像里，所以如果我们要用精确的位置和速度来描述某个物体的话，那么这在描述电子时是行不通的。

[英文](#)

假如在 t_1 时刻，我们按照最适宜的方式把不确定度分配给位置和速度，那么我们会发现在一秒钟以后（ t_2 时刻）电子位置的预测值具有约 5 cm 的不确定度。这就代表着通过任何存在于一秒钟之前的事物，也不可能把对未来位置的不确定度降到这个值以下。如果 t_2 时刻的位置不确定度一直保持这样的程度，那么我们可以说决定论并没有失效，因为那些我们所不能预测的事情（ t_2 时刻电子的精确位置）是没有意义的。但是当这一秒钟消逝之后我们对电子位置的测量能够精确到 0.001 mm 甚至更高。这个精确的位置并不是预先知道的，我们必须等到时机成熟时才能对它进行测量。还要回想起获得这个新的认识是需要付出代价的。除了我们对位置（达到 5 cm ）的大概了解以外，我们还对速度有着相当不错的了解。但是当我们要对位置获得更加精确的认识时，速度就变得非常不确定了。

[英文](#)

也许我们花了很长一段时间来欣赏这种巧妙处理的精细工作原理，正是它在防止我们去寻找比我们本该知道的还要多的事情。但是我并不认为我们应该把这当作是阻止我们去探索更加遥远的未来的自然机制。它们只是数学家们用来保护自己不至做出不可能的预测的手段。当我们提出一个很愚蠢的问题时，数学理论通常不会直接拒绝回答，但会给出一个类似 $\frac{0}{0}$ 的含糊答案，根据那个答案我们得不到任何明确的意思。同样，当我们提出电子明天会在什么地方出现的问题时，数学理论也不会给出直接的回答，“这不好说，因为现在还不能确定”，因为那超出了代数语言的范畴。它所给出的是一个关于 x 和 y 的一般表达式，但可以肯定

的是，在明天到来之前，我们不可能知道这个表达式的含义。

[英文](#)

精神非决定论

似乎很幸运，我没有给自己留出时间来讨论不确定性如何影响了我们对物理世界的总体认识。接下来我很乐意把似乎可以得出的要点做一个简单的概括。

[英文](#)

(1) 如果整个物理世界是可以确定的，那么心理决策（或者至少是有效的心理决策）也一定可以预先确定。因为假如在物理世界里（你的身体也是其中一部分）可以预先确定1月1日你嘴上会叼着一个烟斗，那么你在12月31日为新年是否要戒烟所做的心理斗争显然已经提前有了结果。因而这个新的物理学为我们打开了一扇通向心理现象的不确定性的门，而旧的决定论的物理学则完全把它关在门里。

[英文](#)

(2) 这个门被轻轻地打开了，但显然打开得还不够宽。因为与一个无机的物理系统类比后我们会发现人类活动的不确定性在数量上是可以被忽略的。我们必须通过某种方法，把原子较大的不确定性特征转移到人的活动上来，以代替与无机系统相比几乎可以忽略不计的不确定性。我认为这个难点不是不能克服的，但也决不能低估它。

[英文](#)

(3) 虽然我们也许不能确定中间的步骤，但我们从不怀疑最后的解决方法。如果原子具有不确定性，那么人的思维肯定也会具有同样的不确定性；因为把思维说成比原子更机械的理论是绝大多数人都不愿意接受的。

[英文](#)

(4) 如果人的决定会受到不断出现的新因素的影响，而不仅仅是遗传、培养以及其他先决条件产生的结果，那么人的意识会更加自由吗？对于这样的问题，我们没有给出任何新的答案。这个争论肯定还会无休止地进行下去。就我看来，不确定性还有一个更加重要的方面。它使我们的思想在通过某种模式作决定的时候不会完全被蒙蔽。根据物理世界中的决定论，我的手在写这个讲稿，是由数学物理方程预先确定的进程决定的，我的思想在这里并不重要——一个爱管闲事的人想出了一个与科学问题有关的不相干的故事来解释我的手在做什么——这种解释只会被认为是一种彻头彻尾的谎言。如果思想真的是完全被蒙蔽的，在

这个故事中它是围绕着我们人类的行为编排出来的，那么在这个故事中，我不认为我们会有信心描述物理世界。 [英文](#)

物理学正在变得难以理解。首先是相对论，然后是量子理论，接着是波动力学，它们已经使宇宙发生了转变，使我们眼中的宇宙变得更加奇妙。也许这还不是终点。但是这种变化还有另外一面。朴素的现实主义、唯物主义以及机械论的假设都是较简单的；但是我认为，只有当我们不去理会经验的基本性质而把它跟有意识的生命的反应联系起来的时候，它们看起来才是可信的。这种科学思想上的变革扫清了存在于生命和理论认识之间的深刻矛盾，最近它从决定论中解放出来标志着往前迈进了伟大的一步。我甚至敢说，在物理世界目前的理论中，我们终于达到了能让一个明理的人几乎可以信任的程度。 [英文](#)

（沈乃澂 翻译；葛墨林 审稿）

* 本文是1月4日爱丁顿对数学分会所作的演讲。

† 因为想知道反对放弃决定论的哲学家有什么想法，我参加了亚里士多德学会和哲学学会在1931年7月举办的研讨会。但不幸的是与会者都是非决定论者，研讨会上一个决定论者也没有，在听众中也没有人讨论决定论。我不敢说持决定论观点的哲学家已经不复存在了，这也许应该由哲学界人士来了断。

News and Views

In the early 1930s, physicists were exploring the profound philosophical repercussions of quantum theory. Heisenberg's principle of indeterminacy apparently established clear limitations to determinism in physics. Did an absence of deterministic laws at the microscale undermine cause and effect? In a supplement to this issue, Arthur Eddington considered the "decline of determinism", insisting that indeterministic "secondary" law can still be useful for predicting the future. The author of this essay takes issue with that point, saying that Eddington proclaims the demise of determinism while at the same time supposing its implications for orderly causal links, and even the possibility of prediction, remain. But the essay applauds Eddington's statement that quantum indeterminacy does not imply a universe characterised by unrestrained caprice. [中文](#)

Determinism Defined

SIR Arthur Eddington's characteristically fascinating address on "The Decline of Determinism", which we publish as our Supplement this week, will be welcomed as a clear, unequivocal statement, by a leading authority, on a question which, even among the many revolutionary aspects of the new physics, holds a pre-eminent place for importance and interest. Such a statement is the more necessary because of the almost universal tendency for discussions of determinism to be concerned at bottom with words rather than ideas,

and Sir Arthur has quite properly begun by stating definitely what he means by the determinism which he holds has declined. His thorough analysis leaves little room for disagreement, but many will wonder whether he has not achieved a Pyrrhic victory by conceding to the determinist the substance of his doctrine and destroying only the shadow. “The rejection of determinism is in no sense an abdication of scientific method”, and “indeterministic or secondary law ... can be used for predicting the future as satisfactorily as primary law”. In other words, Sir Arthur does not allow that the first Morning of Creation wrote what the last Dawn of Reckoning shall read, but he allows that it might have read what the last Dawn shall write. Even the most perfervid determinist will scarcely ask more. Furthermore, he acknowledges that he does not know whether Dirac, whose book “goes as deeply as anyone has yet penetrated into the fundamental structure of the physical universe”, is a determinist or not. It would seem, therefore, that the determinism in question cannot be of much importance even in physics. [中文](#)

Physical Inference and Prediction

Apparently, however, in spite of the unqualified statement concerning prediction quoted above, Sir Arthur denies that we can predict the behaviour of electrons more certainly than that of horses, and the importance, to all but the physicist, of the “decline of determinism” therefore depends on the recognition of electrons as bodies co-equal with ordinary physical objects. To establish this he claims that since physical objects, as well as electrons and such particles, are all “inferences”, they differ only in degree and not in kind. We must not, however, be deceived by words. Objects which we see and handle may be, as he says, as inferential as an undiscovered planet inferred from irregularities in the motion of Uranus, but the inferences are of different kinds; otherwise, why, when a planet was seen in a different position from that inferred from the irregularities, was it *without*

question preferred to the “undiscovered” inferential planet? There was not even an instinctive estimate of the “degree” of validity to be attributed to the two “inferences”. Unless Sir Arthur assigns to “direct observation” a status essentially different from that of rational deduction, it is difficult to see how his position can be “in no sense an abdication of scientific method”. All this, however, does not affect determinism in relation to physical objects, and it is to be hoped that Sir Arthur’s plain statement will do much to remove the widespread delusion that modern physics has revealed a universe of unrestrained caprice. [中文](#)

(129, 228-229; 1932)

新闻与观点

在20世纪30年代早期，物理学家们发现量子理论中蕴藏着深刻的哲学内涵。海森堡测不准原理已经证明物理学中的决定论思想存在着明显的局限性。在微观尺度上不存在决定论难道就会有损于因果推理？在为讨论这个问题特设的增刊上，阿瑟·爱丁顿考虑到了“决定论的衰落”，但他坚信非决定论的“次级”原理仍然可以用于预测未来。这篇短文的作者不支持爱丁顿的论点，说他一边宣布决定论的死亡一边又在鼓吹仍然存在有规律的因果联系甚至预测未来的可能性。但作者在文中对爱丁顿的另一个观点表示赞同，即认为量子理论的不确定性并不意味着宇宙处于完全无序的状态之中。 [英文](#)

决定论的界定

在本周《自然》杂志的增刊上刊载了阿瑟·爱丁顿爵士的一篇极具吸引力的题为“决定论的衰落”的演说词。他用清晰准确的语言阐述了一个在新兴物理学各创新领域中显得十分突出的重要问题，他的观点为主要的物理学家所接受。因为大家对决定论的讨论越来越趋向于词藻之争而不是观点的表达，所以阿瑟爵士的这篇文章就显得更加难得了，一开始他就给出了他认为已经衰落了的决定论的明确含义。他的精辟论述没有给异见者留下多少反驳的余地，但很多人怀疑他还未取得皮洛士式的胜利（译者注：指付出重大代价才取得的胜利，古希腊国王皮洛士在公元前280～前279年间曾为打败罗马军队付出了惨重的代价），因为他的学说的基本内容对决定论者是认可的，仅仅否定了一些无关紧要的地方。“摒弃决定论绝不是要放弃科学方法”，“非决定论或次级定律……同样可以像基本定律一样很好地预测未来”。换言之，阿瑟爵士虽不允许在创世纪的第一个早晨就记录下在最后一次大灾难拂晓将看到的一切，但他却相信在创世纪的第一个早晨就能读到最后一次大灾难拂晓所记录下的一切。对于这一点，即使是最坚定的决定论者也不会再过分地要求什

么了。阿瑟爵士还承认自己并不清楚狄拉克是不是决定论者，虽然狄拉克写了一本“比任何人都更深层次地触及到物质世界的基本结构”的书。

看来决定论的观点即便在物理学中也算不上重要了。 [英文](#)

物理推论与预测

然而，尽管上面引用了有关预测问题的无保留的阐述，但阿瑟爵士认为我们对电子行为的预测并不会比对马的行为的预测更准确。因此，对于除物理学家以外的所有人而言，“决定论的衰落”的重要性在于它使人们认识到电子可以被看作是与普通物理对象等同的实体。为了证明这一点，阿瑟爵士声称由于物理对象，包括电子和类似电子的粒子，都是由“推论”得到的，它们只会有程度上的不同，而不会有本质上的差别。然而，我们千万不要被这些文字迷惑。正如他所述，我们可以看到和触摸到的物体也许和从天王星运动的不规则性能推出一颗未知行星的存在一样可以通过推断得到，不过这些推论所属的类别并不相同；否则，为什么当观测到的一颗行星并没有处于由无规则运动推断出的位置上时，人们还是毫无异议地倾向于把它看作就是那颗由推论得到的“未知”行星呢？我们甚至不能直观地估计出这两种“推论”的有效“程度”。除非阿瑟爵士给“直接观测”下一个本质上不同于理性推理的定义，否则很难想象他的立场怎么会是“决不能摒弃科学的方法”。然而所有这些都影响到与物理对象相关的决定论，我们希望阿瑟爵士的平实论述能在很大程度上消除人们普遍存在的错觉，即认为现代物理学揭示的是一个过于变幻无常的宇宙。 [英文](#)

（金世超 翻译；赵见高 审稿）

Artificial Production of Fast Protons

J. D. Cockcroft and E. T. S. Walton

To study the structure of the atomic nucleus, physicists in the early 1930s needed to accelerate probe particles to high energies. Among the first to develop such techniques were John Cockcroft and Ernest Walton in Cambridge. Here they report initial studies using a device for accelerating protons. An electrical discharge in hydrogen gas produced protons, which were then accelerated by high-voltage electrodes in a vacuum tube nearly one metre long, and detected at a fluorescent screen. Cockcroft and Walton measured proton velocities of up to 1.16×10^9 cm/s. The two physicists later used the device to achieve the first artificial splitting of the atom, or “transmutation” of the nucleus, for which they won the 1951 Nobel Prize for physics. [中文](#)

A high potential laboratory has been developed at the Cavendish Laboratory for the study of the properties of high speed positive ions. The potential from a high voltage transformer is rectified and multiplied four times by a special arrangement of rectifiers and condensers, giving a working steady potential of 800 kilovolts. Currents of the order of a milliampere may be obtained at a potential constant to 1–2 percent. [中文](#)

Protons from a discharge in hydrogen are directed down the axis of

two glass cylinders 14 in. in diameter and 36 in. long, and accelerated by the steady potentials of the rectifier. They are then passed into an experimental chamber at atmospheric pressure through a mica window having a stopping power of about 1mm. air equivalent. Luminescence of the air can easily be observed. [中文](#)

The ranges of the protons in air and hydrogen have been measured using a fluorescent screen as a detector. The range in air at S.T.P. of a proton having a velocity of 10^9 cm./sec. is found to be 8.2 mm., whilst the corresponding range for hydrogen is 3.2 cm. The observed ranges support the general conclusions of Blackett on the relative ranges of protons and α -particles, although the absolute values of the ranges are lower for both gases. The ranges and stopping power will be measured more accurately by an ionisation method. [中文](#)

The maximum energy of the protons produced up to the present has been 710 kilovolts with a velocity of 1.16×10^9 cm./sec. and a corresponding range in air of 13.5 mm. at S.T.P. We do not anticipate any difficulty in working up to 800 kilovolts with our present apparatus. [中文](#)

(129, 242; 1932)

J. D. Cockcroft and E. T. S. Walton: Cavendish Laboratory, Cambridge, Feb. 2.

快质子的人工产生

约翰·考克饶夫，欧内斯特·瓦耳顿

为了研究原子核的结构，20世纪30年代的物理学家需要把探测粒子加速到很高的能量。剑桥大学的约翰·考克饶夫和欧内斯特·瓦耳顿是首先利用这类技术的人之一。本文中介绍了他们用质子加速仪所作的研究。首先让氢气放电产生质子，随后质子在近一米长的真空管中被高压电极加速，最后在荧光屏上被检测出来。考克饶夫和瓦耳顿测得的质子速度高达 1.16×10^9 cm/s。后来这两位物理学家利用这个设备首次实现了原子的人工裂变，或称原子核的“蜕变”，他们因此获得了1951年的诺贝尔物理学奖。 [英文](#)

为了研究高速正离子的性质，我们在卡文迪什实验室设立了一个高能实验室。由高压变压器输出的电压，经过特殊设置的整流器和电容器整流后，其值提高为4倍，最后可以得到800千伏的稳定工作电压。当电压的稳定度达到1%~2%时，我们就可以获得毫安级的电流。 [英文](#)

我们使氢电离制得的质子沿着两个直径为14英寸，长为36英寸的玻璃圆管的轴线向下运动，质子被由整流器得到的稳定电压加速。然后它们会通过一个云母窗进入处于大气压下的实验靶室，云母片对质子的阻止作用相当于约1 mm厚的空气。在靶室中很容易观察到空气在质子的轰击下发出冷光的现象。 [英文](#)

利用荧光屏作为探测器可以测量质子在空气和氢气中的射程。一个速度为 10^9 cm/s的质子在处于标准温度和压强下的空气中的射程是8.2 mm，而在相同条件下在氢气中的射程是3.2 cm。我们测量的射程与布莱克特关于质子和 α 粒子相对射程的基本结论一致，但在两种气体中射程的绝对值都偏低。用电离方法测量射程和阻止本领，我们得到的结果会更精确。 [英文](#)

目前能获得的质子的最高能量为710千伏，相应的速度为 1.16×10^9 cm/s，在标准条件空气中的射程为13.5 mm。用我们现在的设备提高到800千伏是完全可以做到的。 [英文](#)

（沈乃澂 翻译；尚仁成 审稿）

Possible Existence of a Neutron

J. Chadwick

Physicists had recently noted that alpha particles hitting a beryllium target produced unknown secondary radiation with great penetrating power. When directed into any material containing hydrogen, this secondary radiation had been found to produce protons. Some physicists suspected that the unknown particles might be high-energy light quanta. But here James Chadwick reports that his studies on the ionisation of nitrogen atoms by collisions with the mysterious radiation point instead to the action of a hitherto unknown particle. Chadwick suggests that the particles have atomic mass one and charge zero: they are what we now call neutrons. It took further experiments to verify the hypothesis, but for this discovery Chadwick won the Nobel Prize in physics in 1935. [中文](#)

IT has been shown by Bothe and others that beryllium when bombarded by α -particles of polonium emits a radiation of great penetrating power, which has an absorption coefficient in lead of about 0.3 (cm.)^{-1} . Recently Mme. Curie-Joliot and M. Joliot found, when measuring the ionisation produced by this beryllium radiation in a vessel with a thin window, that the ionisation increased when matter containing hydrogen was placed in front of the window. The effect appeared to be due to the ejection of protons with velocities up to a maximum of nearly $3 \times 10^9 \text{ cm. per sec.}$ They suggested that the

transference of energy to the proton was by a process similar to the Compton effect, and estimated that the beryllium radiation had a quantum energy of 50×10^6 electron volts. [中文](#)

I have made some experiments using the valve counter to examine the properties of this radiation excited in beryllium. The valve counter consists of a small ionisation chamber connected to an amplifier, and the sudden production of ions by the entry of a particle, such as a proton or α -particle, is recorded by the deflexion of an oscillograph. These experiments have shown that the radiation ejects particles from hydrogen, helium, lithium, beryllium, carbon, air, and argon. The particles ejected from hydrogen behave, as regards range and ionising power, like protons with speeds up to about 3.2×10^9 cm. per sec. The particles from the other elements have a large ionising power, and appear to be in each case recoil atoms of the elements. [中文](#)

If we ascribe the ejection of the proton to a Compton recoil from a quantum of 52×10^6 electron volts, then the nitrogen recoil atom arising by a similar process should have an energy not greater than about 400,000 volts, should produce not more than about 10,000 ions, and have a range in air at N.T.P. of about 1.3 mm. Actually, some of the recoil atoms in nitrogen produce at least 30,000 ions. In collaboration with Dr. Feather, I have observed the recoil atoms in an expansion chamber, and their range, estimated visually, was sometimes as much as 3 mm. at N.T.P. [中文](#)

These results, and others I have obtained in the course of the work, are very difficult to explain on the assumption that the radiation from beryllium is a quantum radiation, if energy and momentum are to be conserved in the collisions. The difficulties disappear, however, if it be assumed that the radiation consists of particles of mass 1 and charge 0, or neutrons. The capture of the α -particle by the Be^9 nucleus may be supposed to result in the formation of a C^{12} nucleus and the emission of the neutron. From the energy relations of this process the

velocity of the neutron emitted in the forward direction may well be about 3×10^9 cm. per sec. The collisions of this neutron with the atoms through which it passes give rise to the recoil atoms, and the observed energies of the recoil atoms are in fair agreement with this view. Moreover, I have observed that the protons ejected from hydrogen by the radiation emitted in the opposite direction to that of the exciting α -particle appear to have a much smaller range than those ejected by the forward radiation. This again receives a simple explanation on the neutron hypothesis. [中文](#)

If it be supposed that the radiation consists of quanta, then the capture of the α -particle by the Be^9 nucleus will form a C^{13} nucleus. The mass defect of C^{13} is known with sufficient accuracy to show that the energy of the quantum emitted in this process cannot be greater than about 14×10^6 volts. It is difficult to make such a quantum responsible for the effects observed. [中文](#)

It is to be expected that many of the effects of a neutron in passing through matter should resemble those of a quantum of high energy, and it is not easy to reach the final decision between the two hypotheses. Up to the present, all the evidence is in favour of the neutron, while the quantum hypothesis can only be upheld if the conservation of energy and momentum be relinquished at some point.

[中文](#)

(129, 312; 1932)

J. Chadwick: Cavendish Laboratory, Cambridge, Feb. 17.

可能存在中子

詹姆斯·查德威克

物理学家们最近指出： α 粒子在撞击铍靶之后能够产生一种穿透力很强的未知次级辐射。他们发现当这种次级辐射射向含氢物质时会有质子生成。一些物理学家怀疑未知粒子可能就是高能光子。但在这篇文章中，詹姆斯·查德威克报告了氮原子与这种神秘射线碰撞后所产生的离子化现象，结果表明它更像是一种迄今未知的粒子。查德威克认为这种粒子的原子量为1，电荷数为0：我们现在把它们称为中子。虽然要验证这一假说还需要进一步的实验，不过查德威克因此而获得了1935年的诺贝尔物理奖。 [英文](#)

博特等人曾指出，当用钋元素放射产生的 α 粒子轰击铍元素时，铍元素会释放出一种穿透力极强的射线，铅对这种射线的吸收系数约为 0.3 cm^{-1} 。最近，约里奥-居里夫妇发现，在一个具有薄窗的容器中测量这种铍辐射导致的电离时，如果在薄窗前放置含氢的物质，电离就会增强。这种现象似乎是由实验中有速度最大值接近于 $3 \times 10^9 \text{ cm/s}$ 的质子发射出来所致。他们认为能量是通过一个类似于康普顿效应的过程转移给质子的，并估算出这种铍辐射的量子能量为 $50 \times 10^6 \text{ eV}$ 。 [英文](#)

为了研究从铍元素中激发出的这种射线的性质，我利用真空管计数器做了一些实验。这种真空管计数器由一个连接到放大器的小电离腔组成。质子或 α 粒子进入电离腔后迅速产生离子的情况可以通过示波器显示的偏转来记录。这些实验表明，该射线轰击氢、氦、锂、铍、碳、空气、氩时都能发射出粒子。从射程和致电离能力来看，氢中发射出来的粒子类似于速度高达约 $3.2 \times 10^9 \text{ cm/s}$ 的质子。其他元素中发射出来的粒子具有很高的致电离能力，看上去像是每种元素的反冲原子。 [英文](#)

如果我们将这一质子发射过程视作能量为 $52 \times 10^6 \text{ eV}$ 的量子康普

顿反冲过程，那么在类似的过程中产生的氮的反冲原子的能量应该不大于400,000 eV，其产生的离子数应该不多于10,000，常温常压下这种原子在空气中的射程应该约为1.3 mm。而事实上，一些氮的反冲原子至少产生了30,000个离子。在与费瑟博士合作进行的实验中，我在膨胀室中观察到了反冲原子，其在常温常压下的射程（目测）有时能达到3 mm。

[英文](#)

如果碰撞过程中能量和动量都是守恒的，那么如果假定铍元素中释放出的这种射线是量子化的，就很难解释上述结果以及我在这项工作中得到的其他一些结果。然而，如果假设这种射线是由一种质量为1，电荷为0的粒子（中子）组成的，那么这些困难将不复存在。我们可以设想， Be^9 原子核俘获 α 粒子后产生了一个 C^{12} 原子核并释放出中子。根据这一过程的能量关系，可以得出朝前方发射的中子的速度刚好约为 3×10^9 cm/s。这一中子穿过物体时与物体中的原子碰撞产生了反冲原子，通过实验对反冲原子能量进行观测得到的结果与这一观点基本吻合。此外，我还观测到，用与激发 α 粒子方向相反的这种射线轰击氢后发射出的质子的射程要比用正向射线轰击得到的质子的射程短得多。这一实验结果同样可以用中子假说来简单解释。

[英文](#)

如果假设这种射线是由量子组成的，那么 Be^9 原子核俘获 α 粒子后将形成一个 C^{13} 原子核。对 C^{13} 质量亏损的精确测量结果表明，这一过程中释放出的量子的能量不可能大于 14×10^6 eV。因此，对于目前观测到的实验现象我们很难将其归因于这样一种量子。

[英文](#)

可以预计，中子穿过物体时产生的很多效应都应该与高能量子产生的效应相似，因此对这两种假说的最终取舍并不容易。到目前为止，所有的证据都更倾向于中子假说，而量子假说只有在放弃能量和动量守恒原理的某些情形下才会得到人们的支持。

[英文](#)

（曾红芳 翻译；刘纯 审稿）

Determinism

J. B. S. Haldane

Arthur Eddington's essay on the decline of determinism provoked strong responses. The biologist J. B. S. Haldane here criticizes Eddington's remarks about human behaviour — specifically, that if the behaviour of atoms is indeterminate, then the human mind must also be. It was then considered that behaviour may be correlated between identical twins. Haldane points out that if one such twin breaks the law during a certain period, the chance that his twin will do so may be as high as 0.875. (These data were almost certainly flawed.) Eddington was effectively claiming that no amount of extra information could turn such a prediction into a certainty. But Haldane complains that this assertion is little more than an a priori pronouncement, unsupported by evidence. [中文](#)

IN his address on the decline of determinism,¹ Sir Arthur Eddington enunciates a very curious equation. "If the atom has indeterminacy, surely the human mind will have an equal indeterminacy; for we can scarcely accept a theory which makes out the mind to be more mechanistic than the atom." This statement will not bear too close an examination even from a non-quantitative point of view. Thus an attempt by myself to solve even a simple wave equation might lead to any of a large number of results; a similar attempt by Sir Arthur Eddington would lead to the correct solution with a high degree of

probability. I do not think that this proves that his mind is more mechanistic than my own, whatever that may mean. Actually it is generally regarded as a compliment to describe a person as reliable, that is, to suggest that his conduct is predictable. 中文

Fortunately, however, quantitative data exist which seem to show that, as regards moral behaviour, some minds are decidedly more determined than are some atoms as regards radiative behaviour. Consider a given man M_1 , and the probability p that between times T_1 and T_2 he will commit an action such as to lead to his imprisonment for a breach of the law. If we have no further information regarding M_1 , p is in most communities a small number, less than 0.01. If, however, M_1 has a monozygotic twin M_2 brought up in the same environment up to the age of 14, and M_2 is known to have been imprisoned for crime between the ages of 16 and 40, we can infer with a fairly high degree of probability that M_1 , who has an identical nature and a similar nurture, has been or will be imprisoned between the same ages. Judging from Lange's² results, p is about 0.875 in south Germany when we have the above amount of information. If we increase the amount of information, for example, by excluding cases where M_2 has suffered from head injury, the value of p is raised still further. Now, if it could be shown that with sufficient information p became unity in a case of this kind, we should, I take it, have proved the determinacy of some kinds, at least, of moral choice. Actually the most that scientific method can do is to prove $p > 1 - \epsilon$. If Sir Arthur Eddington is correct, then no matter how complete our information, ϵ tends to a finite limit which is not very small. Clearly no amount of observation could prove it to be zero. But if it could be shown to be less than 0.01, we could neglect it to a first approximation in ethical theory, and if it proved to be less than 10^{-6} we might hazard the guess that the behaviour of human beings showed no more indeterminacy than that of other systems composed of about 2×10^{27} atoms. 中文

I think that it is a legitimate extrapolation from the existing data that if we used all the available data in the above case, ϵ would be less than 0.05. It seems unfortunate that any attempt should be made to prejudge, on philosophical or emotional grounds, the magnitude of a quantity susceptible of scientific measurement. But from the heuristic point of view the deterministic theory has the advantage that it could be disproved, and would be if ϵ tended to a finite limit as the amount of available information increased indefinitely. On the other hand, indeterminism cannot be disproved unless its supporters state the value of ϵ , which they have so far carefully avoided. When the truth about human behaviour is discovered, it will probably appear that philosophers of all schools had failed to predict it as completely as they failed to predict Heisenberg's uncertainty principle. Human behaviour is a subject for scientific investigation rather than *a priori* pronouncements. [中文](#)

(129, 315-316; 1932)

J. B. S. Haldane: Royal Institution, Albemarle Street, London, W.

References:

1. *Nature*, **129**, 240 (Feb. 13, 1932).
2. *Crime as Destiny* (1931).

决定论

约翰·波顿·桑德森·霍尔丹

阿瑟·爱丁顿的那篇关于决定论在衰落的短文引起了强烈的社会反响。生物学家霍尔丹批驳了爱丁顿关于人类行为的观点，尤其是他认为：如果原子的运动是不可确定的，则人类的思想也不例外。随后霍尔丹列举了同卵双生双胞胎在行为上具有相关性的例子。他说如果其中的一个在某段时间内触犯了法律，那么另一个会触犯法律的可能性高达0.875。（这个数据肯定有问题。）爱丁顿指出这种说法缺少实际的证据。但霍尔丹辩解说爱丁顿的说法纯粹是由推理得到的结果，并没有得到实践上的验证。 [英文](#)

阿瑟·爱丁顿爵士在他的关于决定论的衰落^[1]的讲话中提到了一个非比寻常的对等关系，“如果原子具有不确定性，那么人的思维肯定也会具有同样的不确定性；因为把思维说成比原子更机械的理论是绝大多数人都不愿意接受的。”即便从非定量的角度上看，这种说法与事实也有一定的差距。比如：我在试图解一个很简单的波动方程时也许会得到众多解中的任意一个；而阿瑟·爱丁顿爵士在解同样的方程时会得到可靠性更高的解。我不会因此而认为他的思维比我的思维更机械，不管多么地像是这回事。事实上人们在说一个人可靠时通常是在称赞他，也就是说，他的行为具有可预见性。 [英文](#)

然而，幸运的是，定量数据似乎表明，就道德行为而言，某些人的思想意识确实比一些原子的辐射行为更容易确定。对于某一个人 M_1 ，在 T_1 与 T_2 之间的任意时刻内，这个人付诸一个行动的概率为 p ，比如说他会因违反法律而被监禁。如果我们不了解有关 M_1 的更多情况，则 p 对绝大多数人来说只是一个很小的数，小于0.01。然而，如果 M_1 有一个同卵孪生兄弟 M_2 ，他们在相同的环境下一直长到14岁，且已知 M_2 在16岁至

40岁之间曾因犯罪被监禁过，那么我们就可以认为： M_1 的天性与 M_2 相同，后天培养与 M_2 相似，所以他很有可能在相同的年龄段内也曾被监禁过或将要被监禁。根据兰格^[2]的研究结果，当我们已知以上信息时，在德国南部 p 约为0.875。如果我们能了解更多的情况，例如，知道 M_2 未曾有过头部损伤，则 p 的值还会更大一些。在这类情况下，如果我们了解的信息量足够多，可以把 p 的值取为1，我认为，这说明我们已经证明了某种决定论的存在，至少是在道德选择的层面上。实际上，科学研究的主要任务就是要证明 $p > 1 - \varepsilon$ 。如果阿瑟·爱丁顿爵士是正确的，则不管我们掌握的信息多么全面， ε 都将是一个比较大的有限数。显然再多的观测结果也不能证明 ε 为零。但如果能说明 ε 的值小于0.01，则在伦理学理论的一级近似中我们就可以把它忽略掉，如果能证明 ε 小于 10^{-6} ，我们也许可以大胆地说人类的行为不会比包含约 2×10^{27} 个原子的系统更难以预测。

英文

我认为从现有数据进行的推理是合理的，如果我们利用上述事件中的所有可用信息，那么 ε 的值会小于0.05。但遗憾的是：在哲学或情感的范畴内，对所有能够用科学方法测量的量进行预测都只是一种臆断。从发现的角度上看，决定论的优点是它可以被证伪，当可获得的信息量越来越不确定， ε 趋于一个有限的值时，我们就应该认为该命题不成立。从另一方面来说，非决定论是不能被证伪的，除非其支持者能够明确规定一个 ε 值，而这一点正是他们一直谨慎回避的。当人类行为的真正规律性被发现时，很可能所有学派的哲学家都没能完全预测出来，就像他们没有预测到海森堡测不准原理的出现一样。人类的行为是科学研究的一门学问，而不是先验的臆断。

英文

（沈乃澍 翻译；李淼 审稿）

Determinism

Lewis F. Richardson

The newly discovered principle of quantum indeterminacy inspired considerable philosophical discussion, and even a few attempts to apply it to human nature and the unpredictability of the individual human action. Here Lewis Fry Richardson writes to ridicule the latter proposition. Is it really necessary, he asks? Science is capable of making accurate predictions, as of the motion of a pendulum, for example, but only if no person interferes with it. The dynamics of something as large as the Moon can be treated with mathematical precision, precisely because no one can interfere with it. But when it comes to human action itself, we can never be sure that one person will not interfere with the workings of their own mind. [中文](#)

Is it really necessary to appeal to anything so *recherché* as Heisenberg's Principle of Indeterminacy in order to justify anything so familiar as personal freedom of choice? This question arises on reading Sir Arthur Eddington's interesting address in *Nature* of Feb. 13. Consider any one of the laws of physics commonly verified in the laboratory, say $T=2\pi\sqrt{l/g}$ for a simple pendulum. If, while one student is observing the pendulum, another student were to knock it about, the observations might misfit the formula. And so in general: the accepted laws of physics are verified only if no person interferes with the apparatus. We cannot interfere with the moon, because it is

so massive and so far away: and that is part of the reason why the motion of the moon is almost deterministic; the “almost” referring to the extremely small Heisenbergian indeterminacy. But there is no great mass or great distance to prevent John Doe interfering with his own brain in the act of making his decision to buy a house from Richard Roe. [中文](#)

(129, 316; 1932)

Lewis F. Richardson: The Technical College, Paisley, Feb. 13.

决定论

刘易斯·理查森

新发现的量子测不准原理引发了哲学上的大讨论，有些人甚至用它来解释人类的本性以及个人行为的不可预知性。在这篇文章中，刘易斯·弗赖伊·理查森嘲讽了后者的观点。他认为没有必要用科学来预知人的行为。对于一个钟摆的运动情况，科学是可以准确预测的，但前提是在没有人干扰的情况下。月球等大型天体的动力学也可以通过数学方法精确预测，这也是因为没有人能干涉它运动的缘故。但是当论及人类的行为本身时，我们无法保证一个人不对自己的意识施加影响。 [英文](#)

为了说明像个人选择自由这样熟悉的事也有必要求助于学究式的海森堡测不准原理吗？这个问题是我在阅读阿瑟·爱丁顿爵士于2月13日发表在《自然》杂志上的演说词时联想到的。对于任意一个在实验室里就可以证实的物理定律，比如一个单摆的周期， $T=2\pi\sqrt{l/g}$ ，如果当一个学生观察单摆的时候，另一个学生撞了一下这个摆，则观测结果可能就会与公式不符。所以可以这么说：大家普遍接受的物理定律只有在没有人干扰实验设备的情况下才能被证实。我们无法干扰月球，因为它的质量很大，而且离我们又很远：这就是为什么我们基本上可以预测月球运动的一部分原因；称“基本上”是因为确实存在极小的海森堡不确定性。但是再大的质量或再远的距离也不能阻止约翰·多伊考虑是否要从理查德·罗那里买一幢房子。 [英文](#)

（沈乃澍 翻译；李森 审稿）

Disintegration of Lithium by Swift Protons

J. D. Cockcroft and E. T. S. Walton

Using their recently developed proton accelerator, Cockcroft and Walton had begun experimenting on materials placed in the path of the proton beam. Here they report experiments with lithium. Scintillations on a mica window in the side of the vacuum tube, due to particle impacts, grew more frequent with increasing acceleration voltage. The physicists deduced that these particles were alpha particles, suggesting that lithium nuclei of atomic mass 7 in the target were absorbing protons and becoming unstable nuclei of atomic mass 8, which subsequently split apart into two alpha particles. This was the first observation of the artificial transmutation of an atomic nucleus. [中文](#)

IN a previous letter to this journal¹ we have described a method of producing a steady stream of swift protons of energies up to 600 kilovolts by the application of high potentials, and have described experiments to measure the range of travel of these protons outside the tube. We have employed the same method to examine the effect of the bombardment of a layer of lithium by a stream of these ions, the lithium being placed inside the tube at 45° to the beam. A mica window of stopping power of 2 cm. of air was sealed on to the side of the tube, and the existence of radiation from the lithium was investigated by the scintillation method outside the tube. The

thickness of the mica window was much more than sufficient to prevent any scattered protons from escaping into the air even at the highest voltages used. [中文](#)

On applying an accelerating potential of the order of 125 kilovolts, a number of bright scintillations were at once observed, the numbers increasing rapidly with voltage up to the highest voltages used, namely, 400 kilovolts. At this point many hundreds of scintillations per minute were observed using a proton current of a few microamperes. No scintillations were observed when the proton stream was cut off or when the lithium was shielded from it by a metal screen. The range of the particles was measured by introducing mica screens in the path of the rays, and found to be about eight centimetres in air and not to vary appreciably with voltage. [中文](#)

To throw light on the nature of these particles, experiments were made with a Shimizu expansion chamber, when a number of tracks resembling those of α -particles were observed and of range agreeing closely with that determined by the scintillations. It is estimated that at 250 kilovolts, one particle is produced for approximately 10^9 protons. [中文](#)

The brightness of the scintillations and the density of the tracks observed in the expansion chamber suggest that the particles are normal α -particles. If this point of view turns out to be correct, it seems not unlikely that the lithium isotope of mass 7 occasionally captures a proton and the resulting nucleus of mass 8 breaks into two α -particles, each of mass four and each with an energy of about eight million electron volts. The evolution of energy on this view is about sixteen million electron volts per disintegration, agreeing approximately with that to be expected from the decrease of atomic mass involved in such a disintegration. [中文](#)

Experiments are in progress to determine the effect on other elements

when bombarded by a stream of swift protons and other particles.

[中文](#)

(**129**, 649; 1932)

J. D. Cockcroft and E. T. S. Walton: Cavendish Laboratory, Cambridge, April 16.

Reference:

1. *Nature*, **129**, 242 (Feb. 13, 1932).

由快质子引起的锂衰变

约翰·考克饶夫，欧内斯特·瓦耳顿

考克饶夫和瓦耳顿利用他们最近研制的质子加速器开始对放在质子束路径中的物质进行实验。他们在此报告了用锂做实验的结果。粒子的碰撞会在真空管侧面的云母窗上发出闪烁，加速电压越大，发出闪烁的次数就越多。物理学家们推测这些粒子就是 α 粒子。他们指出靶中原子量为7的锂核因吸收质子而变成原子量为8的不稳定核，随后分裂成2个 α 粒子。这个实验使人类第一次观测到了一个原子核的人工裂变。 [英文](#)

在先前写给《自然》杂志的一封快报^[1]中，我们描述了一种通过加高压获得能量高达600千伏快质子稳定流的方法，同时还描述了测量这些质子在真空管外的射程的实验。现在我们把锂片放在真空管中，与粒子束成 45° 角。然后用同样的方法测量了快质子束轰击锂片产生的效应。在真空管的端口贴有一个阻止本领相当于2 cm厚空气的云母窗片。锂发出的辐射可以在真空管外用闪烁方法来测量。云母窗非常厚，它在所加电压达到最高值时足以阻挡散射的质子泄漏到空气中。 [英文](#)

当加速电压达到125千伏时，我们立即看到了许多明亮的闪烁光，闪烁的次数随电压迅速增加，直到所使用的最高电压，即400千伏。在质子流为几个微安的情况下，我们在这时每分钟可以观测到数百次的闪烁。但当质子流被阻断或当锂片被一块金属屏蔽时，任何闪烁都看不到了。我们用在辐射路径上放置的云母片来测量粒子的射程，在空气中测量到的射程为8 cm，这个值基本上不会随加速电压的变化而改变。

[英文](#)

为了说明这类粒子的性质，我们用清水的膨胀室做实验，发现许多粒子的径迹类似于 α 粒子的径迹，而射程与用闪烁法测量的数值非常接

近。我们估计在加速电压为250千伏时，大约每 10^9 个质子可以产生一个粒子。 [英文](#)

在膨胀室中看到的闪烁亮度和径迹密度说明辐射粒子就是普通的 α 粒子。假如这个判断是正确的，那么质量数为7的锂同位素就可能俘获1个质子并在产生了质量数为8的原子核后又分裂成2个 α 粒子，每个 α 粒子的质量数为4且具有约为 8×10^6 eV的动能。按照上述观点，每次分裂将产生约 1.6×10^7 eV的能量，这与根据衰变过程中原子质量下降推算出的结果大致相等。 [英文](#)

我们正在用实验测定快质子束和其他粒子束轰击别的元素产生的效应。 [英文](#)

（沈乃澍 翻译；江丕栋 审稿）

The Cry of Tin

Tin has been long known to release a “shriek” or “cry” when bent. Here Bruce Chalmers of University College London attempts to move beyond the vague notion that the sound is caused by the grinding of crystals against one another during deformation. He proposes that it stems from the phenomenon of twinning, in which two crystals share some of the same crystal lattice points, typically with one crystal being a mirror image of the other. Chalmers, who became a celebrated crystallographer, was then working with E. N. da C. Andrade, a pioneer in the study of the crystal structures of metals. Andrade endorses Chalmer’s work here, saying that it may be important for understanding the general phenomenon of twinning. [中文](#)

IT is an observation of respectable antiquity that when a bar of tin is bent it emits a characteristic creaking, known as the “cry of tin”. According to Mellor¹, who is one of the few authorities to refer to the subject, the cry “is supposed to be produced by the grinding of the crystals against one another during the bending of the metal”, and I have been unable to find in the literature any more definite explanation of its origin. In the course of some experiments which I have been carrying out with Prof. E. N. da C. Andrade on single crystal wires I have made observations which, I think, make possible a rather more precise attribution of the sound. [中文](#)

I have obtained the cry with cadmium as well as with tin. When single

crystal wires of these metals are stretched, the deformation takes place in two stages, a slip on the glide planes, which constitute in both cases a unique system, being succeeded by a mechanical twinning on a specified plane. The twinning does not take place until after a definite amount of glide extension has occurred, which enables the two phenomena to be studied separately. 中文

With single crystal wires no sound is produced during the glide stage of extension, but with both metals twinning is accompanied by the characteristic creaking or tearing sound. The same sound also occurs when such wires are violently bent or twisted, a process which gives rise to the surface marking characteristic of twinning, although it does not allow the separation of twinning from other effects in the way that simple extension does. 中文

The tin with which the phenomenon is normally observed is in a polycrystalline state. Although the cry occurs when polycrystalline cast rods of both tin and cadmium are bent, drawn wires of small diameter do not give it unless they are annealed, or, in other words, the production of the sound depends on the size of the crystallites being greater than a certain minimum—larger crystals, of course, being subjected to more severe strain when the metal is bent. It is reasonable to suppose that the cry is an accompaniment of twinning in the case of the polycrystalline state as well as in the single crystal state. 中文

Preliminary measurements on cadmium indicate that whereas the heat evolved in the twinning is of the order of 0.1 calories per gram, less than one-tenth of this amount is produced during the whole extension accompanying gliding, although this extension is considerably greater than that due to the twinning. The measurements, which are being followed up with more accurate methods, give, at present, only rough approximations, but suffice to establish clearly this very much greater heating which accompanies twinning. This observation suggests that

some of the mechanical energy that is supplied to the lattice to cause twinning is afterwards liberated as heat energy and, in particular cases, as sound energy, the cry of tin and cadmium being a manifestation of the latter. 中文

It may be added that while a cry can be produced from zinc, which crystallises in the hexagonal system and twins readily, I have not been able to produce a cry with any metal crystallising in a cubic system, for which twinning does not take place. 中文

Bruce Chalmers

* * *

The observations of Dr. Chalmers described in the above letter, which are being followed up, seem to me likely to prove of considerable importance for elucidating the problem of twinning. The generation of heat agrees with the view that, in twinning, the molecules, when sufficient energy is applied, slip from one equilibrium position to another, about which they then execute heavily damped vibrations, the energy of vibration dissipating itself in heat and probably in radiation of a frequency of the *Reststrahlen* order. The sound indicates that the twinning does not take place over the whole region of twinning simultaneously, for the sound frequency is much too low to be connected with the vibration of molecules or molecular units, but is propagated from layer to layer with a velocity or velocities of the order of sound velocity. It is possible that in the case of substances where sudden twinning is unaccompanied by audible sound, the sound exists, but is of too high a frequency to be heard. 中文

E. N. da C. Andrade

(129, 650-651; 1932)

Reference:

1. *Complete Treatise of Inorganic Chemistry*, 7, 296.

锡叫

人们很早以前就知道金属锡在弯曲时会发出“尖叫声”或“哭泣声”。通常认为这种现象是由晶体在变形过程中的相互挤压造成的，而伦敦大学学院的布鲁斯·查默斯在这篇文章中试图给出更加清晰的解释。他认为叫声源于孪晶现象，即两个晶体共用晶格点阵上的某些点，尤其是当一个晶体作为另一个晶体的镜像存在时。当年查默斯与研究金属晶体结构的先驱者——安德雷德一起工作，后来他自己也成为了一位著名的晶体学专家。安德雷德对查默斯在这方面的研究表示认同，他说这对于认识孪晶中的普遍现象具有非常重大的意义。

[英文](#)

这是一个相当古老的发现，当一根锡棒弯曲时会发出特有的吱吱嘎嘎声，即通常所称的“锡叫”。梅勒^[1]是少数谈到过这一主题的作者之一，他认为这种声音“可能是金属在弯曲时由晶体彼此之间的相互摩擦而产生的”，但是我在文献中始终没能找到关于其起源的更为确定的解释。在我与安德雷德教授合作进行的关于单晶丝的实验过程中，曾经进行了一些我认为能够更精确地解释该声音的观测。

[英文](#)

我发现镉也可以发出和锡一样的声音。在将这些金属的单晶丝拉伸时，变形过程分两个阶段，先是沿滑移面上滑移，这滑移存在于二个阶段中，随后是在某一特定晶面上发生机械孪生。孪生要在特定量的滑移形变出现后才会发生，这使得两种现象可以分别得到研究。

[英文](#)

在滑移形变引起的延伸阶段，单晶丝没有产生声音，但是两种金属孪生时却伴随有特征的碾轧声或撕扯声。同样的声音在将这些金属丝强力弯曲或扭转时也出现了，这一过程产生了孪晶所特有的表面斑纹，尽管它还不足以将孪晶化与简单延伸过程中产生的其他效应相区分。

[英文](#)

通常观测到这种效应时所用的锡处于多晶态。尽管锡和镉的多晶铸棒在弯曲时都会发出叫声，小直径的拉制金属丝却只有在退火后才能发出声音，或者换一种说法，这种声音的产生需要晶粒的尺寸大于某一特定下限——当然，较大的晶体在金属弯曲时要经受更为强烈的应变。有理由认为，在多晶态和单晶态中的发声都伴随着孪生的发生。 [英文](#)

对镉的初步观测结果，在孪生过程中所产生的热量只有0.1 cal/g的数量级，不足由滑移引起的整个延伸过程中所产生热量的1/10，虽然，这种延伸明显大于孪生本身所导致的延伸。目前，以更为精确的方法进一步开展的观测只给出了粗略的近似值，但已足够清晰地确认这一伴随孪生过程而产生的较大热量。这一观测结果意味着，一些提供给晶格以产生孪晶的机械能后来以热能和（在某些特殊情况下）声能的形式释放出来，锡和镉的发声就是后一种情况的体现。 [英文](#)

还可以补充的是，以六方晶系形式结晶并且容易形成孪晶的锌能够产生发声，但我一直无法用以立方晶系形式结晶的任何金属来产生声音，它们不产生孪晶。 [英文](#)

布鲁斯·查默斯

* * *

上面这封信中所描述的查默斯博士即将进一步展开的观测，在我看来，很有可能会被证明对于孪晶问题的阐明具有相当的重要性。热的产生与下面的看法一致，即孪晶中的分子在外加足够能量时会从一个平衡位置滑移到另一个平衡位置，并在该位置发生强烈的阻尼振荡，振荡的能量以热的形式以及很可能以与剩余射线的频率相当的辐射形式消散。对声音的研究表明，孪晶化并不是在整个孪晶区域中同时发生的，因为声音的频率实在太低而无法与分子或分子单元的振动联系起来，只能以声速或具有声速水平的速度沿层间传播。有可能会有这样的情况，即突然形成的孪晶没有伴随着可听到的声音；声音是存在的，但是因其频率过高而无法被听到。 [英文](#)

安德雷德

(王耀杨 翻译；沈宝莲 审稿)

The Neutron Hypothesis

D. Iwanenko

Chadwick's hypothesis of the neutron rapidly drew attention from other physicists. Electrons were often expelled from the nucleus during radioactive decay, implying that they must reside somewhere within it. Here Russian physicist Dmitri Iwanenko suggested that electrons change their nature when inside the nucleus, losing their quantum-mechanical spin or magnetism. Inside the nucleus, they may be packed up inside neutrons or alpha particles (which were then still taken to be "elementary" particles along with protons and electrons). Indeed, beta decay involves the decomposition of a neutron into a proton and electron. [中文](#)

DR. J. Chadwick's explanation¹ of the mysterious beryllium radiation is very attractive to theoretical physicists. Is it not possible to admit that neutrons play also an important rôle in the building of nuclei, the nuclei electrons being *all* packed in α -particles or neutrons? The lack of a theory of nuclei makes, of course, this assumption rather uncertain, but perhaps it sounds not so improbable if we remember that the nuclei electrons profoundly change their properties when entering into the nuclei, and lose, so to say, their individuality, for example, their spin and magnetic moment. [中文](#)

The chief point of interest is how far the neutrons can be considered as elementary particles (something like protons or electrons). It is easy to calculate the number of α -particles, protons, and neutrons for a

given nucleus, and form in this way an idea about the momentum of nucleus (assuming for the neutron a moment $\frac{1}{2}$). It is curious that beryllium nuclei do not possess free protons but only α -particles and neutrons. [中文](#)

(129, 798; 1932)

D. Iwanenko: Physico-Technical Institute, Leningrad, April 21.

Reference:

1. *Nature*, **129**, 312 (Feb. 27, 1932).

中子假说

德米特里·伊万年科

查德威克的中子假说很快引起了其他物理学家的注意。在发生放射性衰变时原子核中经常会放出电子，这意味着电子肯定位于原子核内部的某个位置上。俄罗斯物理学家德米特里·伊万年科认为当电子位于原子核内部时性质会发生变化，不再具有量子力学的自旋和磁性。在原子核的内部，电子可能堆积在中子或 α 粒子（那时人们还以为 α 粒子是与质子和电子并列的“基本”粒子）里。确实在 β 衰变中就包括一个中子分解成一个质子和一个电子的过程。 [英文](#)

查德威克博士关于神秘铍辐射的解释^[1]对于理论物理学家来说很有吸引力。难道不能认为中子在原子核的构成中也起着重要的作用，核电子都被包裹于 α 粒子或中子之中？因为缺乏关于原子核的理论，这一假设当然无法得到确认，但是如果我们记得核电子在进入核时其性质会发生根本性的变化，可以说失去了其诸如自旋和磁矩等个体特征，那么这个假设也许听起来并不是那么不可能。 [英文](#)

我们需要关注的要点在于中子在多大程度上可以被看作是基本粒子（类似于质子或电子）。对于一种给定的核，很容易计算出其中 α 粒子、质子和中子的数目，并用这种方式形成一种关于核矩的概念（假定中子的核矩为 $1/2$ ）。奇怪的是，铍核并不具有自由质子而只有 α 粒子和中子。 [英文](#)

（王耀杨 翻译；刘纯 审稿）

New Evidence for the Neutron

Irène Curie and F. Joliot

The existence of the neutron here receives support from Irène Curie and Frédéric Joliot. Experimenting with particles emitted from lithium bombarded by alpha particles, they found a penetrating power less than that of gamma rays from radioactive decay. Moreover, these particles were absorbed more readily by paraffin than by lead, ejecting protons in the process, indicating that they were not electrons or light quanta (which would not do so because of their small or zero mass). The evidence points to the particles in question being different from previously known radiation. Curie and Joliot completed some of their experiments before Chadwick's, and might have discovered the neutron first had their interpreted them properly. Their early results stimulated Chadwick's own decisive experiments. [中文](#)

SEVERAL important communications dealing with the properties of rays emitted by atomic nuclei when bombarded with α -particles have recently appeared,¹ on which we should like to make a few comments.

[中文](#)

It has been shown by F. Joliot² that the rays emitted by boron under the action of α -particles from polonium are much more penetrating than had originally been indicated. Their penetrating power, while superior to that of the most powerful γ -rays obtained from radioactive sources, is inferior to that of the rays obtained from beryllium

bombarded by α -particles from polonium. This result does not agree with Webster's findings, but agrees with the fact that the protons ejected from boron are slower than those ejected from beryllium. Secondly, we have shown that the ejection of protons is a general phenomenon. By means of the Wilson chamber, we have photographed the paths of the helium nuclei ejected by beryllium rays, and from absorption measurements were able to conclude that other atoms are also ejected. Further, our experiments showed for the first time the important part played by the nuclei in the absorption of the rays emitted by beryllium under the influence of α -particles, a phenomenon which clearly marked them off from all previously known radiation. [中文](#)

J. Chadwick was led simultaneously to the same generalisation concerning the ejection of nuclei, and he put forward the view that the penetrating rays produced by the bombardment of beryllium by α -particles from polonium are neutrons. This interpretation is necessary if energy and momentum are conserved in the collision. [中文](#)

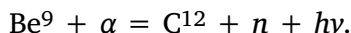
Recent experiments which we have carried out with M. Savel clearly show that the rays emitted by lithium have a penetrating power, in lead, less than that of the γ -rays of polonium (they are completely absorbed by 5 mm. of lead), and that they are much more readily absorbed, at equal surface mass, by paraffin than by lead. This proves that they cannot be of an electronic or electromagnetic nature. Since for various reasons it is extremely improbable that we are dealing with hydrogen nuclei or α -particles (the energy of which would be enormous), these results prove—*independently of the ejection of nuclei and the laws of elastic collisions*—that the rays emitted by lithium under bombardment by α -particles from polonium are different from previously known radiation and are probably neutrons. The above reasoning does not apply to the rays ejected from beryllium, boron, or to those emitted by lithium when bombarded with the α -rays from the

active residue of radium³, because in such cases we do not have γ -rays of equivalent penetrating power, for comparison. 中文

Our latest experiments, in collaboration with M. Savel, indicate that the protons ejected from beryllium form two groups. This suggests that there are also two groups of neutrons (each group not necessarily homogeneous); one group has a range of 28 cm. in air, and an energy of 4.5×10^6 electron volts; the other has a range of about 70 cm. and an energy of approximately 7.8×10^6 electron volts. We find it difficult to reconcile Chadwick's result of a *maximum range* of 40 cm. with the curves which we have obtained for the absorption of protons.

中文

The mass of the neutron calculated by Chadwick⁴ (based upon the experimentally estimated energy of the neutrons from boron), according to the reaction $B^{11} + \alpha = N^{14} + n$,⁵ is about 1.006 (He=4), and the atomic mass of Be⁹, based on the energy of the fast neutrons (7.8×10^6 ev.), is 9.006. This suggests that the binding energy between the two α -particles and the neutron in the Be⁹ nucleus is relatively weak. Further, we know that the rays emitted by beryllium are composed of neutrons and photons, and we may therefore suppose that they are emitted simultaneously according to the equation



中文

The photons of 2 to 4.5×10^6 ev. energy, which we have detected, would correspond to the group of neutrons of maximum energy 4.5×10^6 ev. (protons having a range of 28 cm.). 中文

(130, 57; 1932)

References:

1. Webster, H. C., Chadwick, J., Feather, N., and Dee, P. I., *Proc. Roy. Soc., A*, **136**, 428, 692, 708 and 727 (1932).
2. Joliot, F., *C.R. Ac. Sci.*, **193**, 1415 (1931).
3. Broglie, M. de, and Leprince-Ringuet, L., *C.R. Ac. Sci.*, **194**, 1616 (1932).
4. Chadwick, J., *Proc. Roy. Soc., A*, **136**, 702 (1932).
5. Curie, I., and Joliot, F., *C.R. Ac. Sci.*, **194**, 1229 (1932).

关于中子的新证据

伊雷娜·居里，弗雷德里克·约里奥

中子的存在被伊雷娜·居里和弗雷德里克·约里奥的实验所证实。他们用 α 粒子轰击锂靶使之发射出粒子，然后发现该粒子流的穿透力低于放射性衰变中的 γ 射线。还发现石蜡比铅更容易吸收这些粒子。吸收过程中会放出质子说明它们不是电子或光量子（因为电子和光量子的质量很小或为零）。有证据表明该粒子也不同于以前所熟知的任何辐射。居里和约里奥的实验先于查德威克，如果他们能对实验结果作出正确的解释，那他们也许会首先发现中子。正是他们得出的前期结果引出了查德威克的那个具有决定意义的实验。 [英文](#)

文

最近出现了几篇颇有影响力的论文，内容是关于受 α 粒子轰击的原子核所发射的射线的性质^[1]，对此，我们想发表一些看法。 [英文](#)

约里奥曾指出^[2]，硼在从钋中发出的 α 粒子的作用下发射出的射线比原来对其穿透力的预计值大很多。它们的穿透力大于由放射源得到的最强的 γ 射线，但要低于从钋中发出的 α 粒子轰击铍得到的射线。这一结论与韦伯斯特的研究结果不相符，但是与硼发射的质子比铍发射的质子速度慢的现象一致。其次，我们曾说过发射出质子是普遍存在的现象。我们利用威尔逊云室拍摄了由铍辐射产生的氦核的路径，并通过吸收测量得知其他原子也会发射质子。第三，是我们的实验最先说明原子核在吸收被 α 粒子轰击的铍发射的射线中所起的关键作用，这一现象可以把它们与所有以前知道的辐射明确地区分开来。 [英文](#)

查德威克与我们同时注意到了这一关于核发射的普遍现象，他还提出了以下观点，即用从钋中发出的 α 粒子轰击铍而产生的具有很强穿透力的射线就是中子。如果要保持能量和动量在碰撞中的守恒，就必须接

受这一解释。

[英文](#)

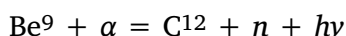
最近我们与萨韦尔共同完成的实验清晰地表明，由锂发射的射线在铅中具有穿透能力，但低于钋发射的 γ 射线的穿透能力（它们能被5 mm厚的铅完全吸收），当表面质量相同时，石蜡对它们的吸收要远远大于铅。这说明它们不可能具有电子或电磁学的特征。我们有许多证据证明在实验中出现的粒子绝对不可能是氢核或 α 粒子（它们的能量很大），这些结果表明：与原子核发射粒子和弹性碰撞定律无关，用由钋衰变得到的 α 粒子轰击锂发出的射线与以前所知的辐射都不相同，这类射线可能是中子。上述推论不适用于由铍和硼发射的射线，也不适用于用由镭的放射性剩余物产生的 α 射线轰击锂而发出的射线^[3]，因为在这几种情况下，我们没有用具有相同穿透力的 γ 射线作为比照。

[英文](#)

我们与萨韦尔合作完成的最新实验说明铍发射的质子可以分为两组。这意味着也存在两组中子（两组中子未必同质）；其中一组在空气中的射程为28 cm，能量为 4.5×10^6 eV；另一组射程约为70 cm，能量约为 7.8×10^6 eV。查德威克的结果是最大射程为40 cm，而我们从质子吸收曲线得到的结论与他的结果并不一致。

[英文](#)

查德威克根据反应式 $B^{11} + \alpha = N^{14} + n$ ^[5]计算出的中子质量^[4]（基于实验测算出的由硼发射的中子能量）约为1.006（He = 4），并从快中子的能量（ 7.8×10^6 eV）推算出Be⁹的原子质量为9.006。这说明Be⁹核内两个 α 粒子与中子之间的结合能相当弱。此外，我们还知道铍发射的射线包括中子和光子，因而我们也许可以假定它们是按照下述反应式同时发出的：



[英文](#)

我们探测到光子的能量在 2×10^6 eV到 4.5×10^6 eV之间，它们应该对应于最大能量为 4.5×10^6 eV的那一组中子（质子的射程为28 cm）。

[英文](#)

（沈乃澍 翻译；朱永生 审稿）

Mechanism of Superconductivity

J. Dorfman

Superconductivity—the conduction of electrical current in cold metals without resistance—was observed in 1911, but lacked an explanation. Many suspected that some kind of coherent behaviour among the electrons must be responsible. Here Russian physicist J. Dorfman explores experimental evidence for analogies between superconductivity and magnetism. He studies the temperature dependence of the thermoelectric effect for lead (where heat creates electricity), and finds a sharp cusp near the superconducting transition temperature, leading him to suspect an analogy between the ferromagnetic and superconducting transitions. Both are now seen to belong to the same class of “critical” transitions, although magnetism per se is not involved in this kind of superconductivity. [中文](#)

IT was often assumed that the transition from normal conductivity to superconductivity may be connected with a kind of “spontaneous coupling” of the conduction electrons. Some authors were even inclined to identify this phenomenon with ferromagnetism. Although this extreme point of view seems to be very improbable, some analogies with ferromagnetism must surely appear if any kind of “spontaneous coupling” between electrons is responsible for superconductivity. For example, in this case the shape of the specific heat curve near the transition temperature must be analogous to that

of ferromagnetic substances in the vicinity of the Curie point. W. Keesom and J. H. van den Ende,¹ and F. Simon and K. Mendelssohn² attempted to discover this anomaly of the specific heat in lead near the transition temperature (7.2° K), but they could not detect any trace of the effect. This result may be interpreted in two ways: either the hypothesis of the “spontaneous coupling” of the conduction electrons in superconductors is completely wrong, or the number of the electrons which are concerned in conductivity is here so small in comparison with the number of atoms that the specific heat anomaly of the conduction electrons cannot be detected with calorimetric methods. [中文](#)

As our measurements have shown, the specific heat anomaly of ferromagnetic bodies at the Curie point is so well pronounced in the thermoelectric effects (Thomson effect), that in spite of some difficulties concerning the sign of this effect, the order of magnitude of the specific heat anomaly can be computed from the purely thermoelectric constants in good agreement with calorimetric measurements. It is natural to try the same method in the domain of superconductivity. The recent investigations by J. Borelius, W. M. Keesom, C. H. Johansson, and J. O. Linde³ of the thermoelectric force for lead and tin at the lowest temperatures permit us to compute the Thomson effect for these metals and to draw conclusions concerning the specific heat anomaly. Fig. 1 represents the Thomson coefficient for lead (as calculated from the experimental data) as a function of temperature. This curve is quite analogous to that of ferromagnetic substances, and it seems quite probable that it represents the general feature of the specific heat of the electrons concerned in the conductivity effects. It is not clear, however, why the temperature of the maximum of this specific heat curve (10.5° K) does not coincide with the transition point (7.2° K). Perhaps theory will be able to explain this discrepancy in the future. [中文](#)

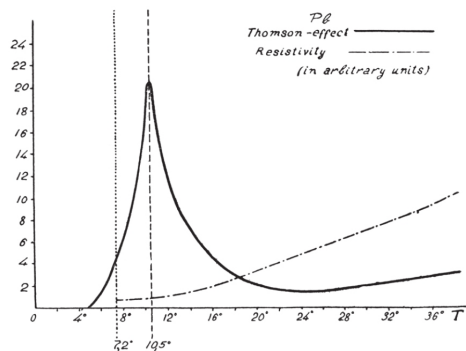


Fig. 1. [中文](#)

From these results two important quantities may be calculated: first, ΔC_ε (the height of the maximum of the specific heat curve), and secondly, ΔW_0 (the energy difference between the normal and the superconducting state at absolute zero), both for one electron. [中文](#)

[文](#)

	ΔC_ε cal./ degree.	ΔW_0 ergs.
Lead	8×10^{-25}	1.7×10^{-17}
Tin	$\sim 10^{-25}$	$\sim 0.6 \times 10^{-17}$

[中文](#)

If the number of the electrons was equal to the number of atoms of lead, the specific heat anomaly could certainly be detected, its numerical value being of the same order of magnitude as the normal specific heat itself. The precision of the calorimetric measurements permits us to determine the upper limit of the number of the electrons involved in the conductivity effects of lead. Actually it seems that the number of the conduction electrons is less than 1/200 of the number of the atoms in this case. [中文](#)

It is well known that magnetic fields destroy the superconductivity, the threshold value of the field H increasing as the temperature is lowered. By extrapolating the experimental data the value of H_0 may be found corresponding to absolute zero. We assume that the

threshold value of the field is given by the condition that the magnetic energy of the electron $|\mu H_0|$ (where μ is the spin moment) is equal to ΔW_0 . [中文](#)

$$|\mu H_0| = \Delta W_0 \qquad (1) \qquad \text{中文}$$

This assumption means that the superconductivity must be destroyed when the energy of the external forces exceeds the energy of the “spontaneous coupling”. Form (1) we may calculate H_0 for lead and tin, and compare them with the experimental results. [中文](#)

	H_0 expt. (gauss).	H_0 calc. (gauss).
Lead	2,000–2,500	2,000
Tin	560	~700

[中文](#)

According to the recent experiments of McLennan and his co-workers,⁴ superconductors cease to be superconducting for high frequency currents if the frequency ν exceeds a certain threshold value. For tin at absolute zero, $\nu \sim 10^9$ may be found by extrapolation of the experimental data obtained at higher temperatures. It is interesting to notice that by assuming

$$h\nu_0 = \Delta W_0 = |\mu H_0| \qquad (2)$$

(where h is Planck’s constant), we obtain for the same metal $\nu_0 = 1 \times 10^9$. [中文](#)

The remarkable coincidence between the observed and the computed data seem to support the general trend of the assumptions developed in this note. It is interesting to notice that the frequency of the Larmor precession corresponding to H_0 is equal to ν_0 ; thus the correlation between the two factors destroying the superconductivity may be found either on the lines of energetics or on the lines of the short time

periods. Which of these interpretations corresponds to the real mechanism remains unsolved at this moment. [中文](#)

(130, 166-167; 1932)

J. Dorfman: Physical-Technical Institute, Sosnovka 2, Leningrad (21), U.S.S.R., May 23.

References:

1. *Comm. Leiden*, 230 d (1930).
2. *Z. Phys. Chem.*, B **16**, H. 1 (1932).
3. *Proc. Amsterdam Acad.*, **34**, No. 10 (1931).
4. *Proc. Roy. Soc., A*, **136**, No. 829, 52 (1932).

超导电性机理

多尔夫曼

超导电性，即某些金属在低温下无阻的传导电流，是1911年被首次观察到的，但没有给出解释。有不少人猜测电子之间的某种相干行为应是产生超导性的原因，在下文中，俄罗斯物理学家多尔夫曼用实验揭示了超导性与磁性之间的相似性。他研究了铅的温度与热电效应（由热生电的现象）的关系，发现在超导转变温度附近存在一个尖点，这使他猜想在铁磁和超导转变之间存在着某种相似性。在今天看来，虽然磁性本身与超导性无关，但两者都属于同种类型的“临界”转变。 [英文](#)

人们通常假设，从正常传导性到超导性的转变可能与导电电子的某种“自发耦合”有关。某些作者甚至倾向于认为超导现象等同于铁磁现象。虽然这个极端的观点似乎不存在成立的可能，但是，如果超导性真的是由电子间的某种“自发耦合”引起的，那么它就一定会表现出与铁磁性类似的行为。例如，超导体的比热曲线在转变温度附近的形状应该与铁磁体的比热曲线在居里点附近的形状相似。凯索姆与范登恩德^[1]，以及西蒙与门德尔松^[2]都试图去揭露铅的比热在超导转变温度（7.2 K）附近的这种反常行为，但是他们都未能探测到这种行为的任何迹象。该结果也许可以从两个角度来解释：要么是由于超导体中导电电子的“自发耦合”假说是完全错误的，要么就是由于在传导性中计入的电子的数目较之原子的数目而言太小，以至于无法用量热法探测出由传导电子引起的比热反常。 [英文](#)

正如我们的测量结果所表明的那样，铁磁体在居里点的比热反常表现在热电效应（汤姆孙效应）上是非常显著的，以至于尽管有关此效应的正负号确定还存在一定的困难，但由纯热电常数计算出来的比热反常

的数量级与量热法的测量值还是符合得很好。人们很自然地想到将这种方法用于超导性领域。最近，博雷柳斯、凯索姆、约翰松与林德^[3]研究了对最低温度下铅和锡的温差电势，这使我们能够计算这两种金属的汤姆孙效应，并可得到关于比热反常的结论。图1给出了铅的汤姆孙系数（由实验数据计算得出）与温度的函数关系。这条曲线和铁磁物质的曲线十分相似，且很可能代表了与传导性效应有关的电子的比热的普遍特征。不过，我们还不清楚为什么这条比热曲线上最大值所相应的温度（10.5 K）与超导转变温度（7.2 K）不一致。也许未来的理论可以解释这一分歧。

英文

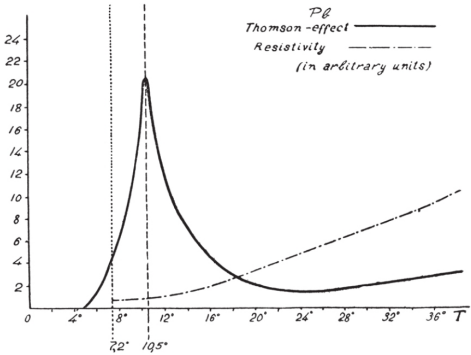


图1 英文

由这些结果可以计算出两个重要的物理量：首先是 ΔC_E （比热曲线上最大值的高度），其次是 ΔW_0 （绝对零度下正常态和超导态的能量差），两者都是针对一个电子。

英文

	ΔC_E 卡 / 度	ΔW_0 尔格
铅	8×10^{-25}	1.7×10^{-17}
锡	$\sim 10^{-25}$	$\sim 0.6 \times 10^{-17}$

英文

倘若铅中的电子数目与原子的数目相等，则比热反常就一定能被探测到，因为它的数值与正常态的比热同量级。根据量热法的测量精度，我们可以确定铅中参与传导效应的电子数目的上限。实际上，导电电子的数目比此情况下原子数目的1/200还要少。

英文

众所周知，磁场会破坏超导性，磁场 H 的阈值随着温度的降低而增大。从实验数据可以推出：临界场 H_0 的值可能与绝对零度有关。我们假设场的阈值通过电子的磁能 $|\mu H_0|$ （ μ 为自旋磁矩）等于 ΔW_0 来确定。

英文

$$|\mu H_0| = \Delta W_0 \quad (1) \quad \text{英文}$$

这个假设意味着：当外力的能量超过“自发耦合”的能量时，超导性一定会被破坏。我们可以由式（1）计算铅和锡的临界场 H_0 ，并把它们与实验结果作比较。

英文

	H_0 的实验值 (高斯)	H_0 的计算值 (高斯)
铅	2,000~2,500	2,000
锡	560	~700

英文

根据麦克伦南及其合作者近期的实验^[4]，如果超导体中高频电流的频率 ν 超过了某一临界值，则超导现象就会消失。从较高温度下的实验数据可以推出，绝对零度下锡的 $\nu \sim 10^9$ 。有趣的是，通过假设

$$h\nu_0 = \Delta W_0 = |\mu H_0| \quad (2)$$

（ h 是普朗克常数），对同一金属我们也可得到 $\nu_0 = 1 \times 10^9$ 。

英文

实验值和计算值的明显致似乎支持了我们在文中提出的假设。有趣的是：对应于 H_0 的拉莫尔进动频率恰等于 ν_0 ；因此，两个破坏超导性的因素之间的关联既可以体现在能量的关系上，也可以体现在短周期的关系上。究竟这些解释中的哪一个对应真正的超导性机理，现在还没有答案。

英文

（王静 翻译；陶宏杰 审稿）

Disintegration of Light Elements by Fast Protons

J. D. Cockcroft and E. T. S. Walton

Here Cockcroft and Walton update their studies of how high-energy protons interact with the nuclei of light elements. Since their report of artificially induced disintegration of lithium, they had improved the sensitivity of their detecting apparatus and extended their study to the element boron. Here they record a huge number of alpha particles created by proton bombardment, suggesting a nuclear reaction in which the boron nucleus boron-11 becomes boron-12 on absorbing a proton, and subsequently disintegrates into three alpha particles. [中文](#)

SINCE the publication of our paper¹ on the disintegration of elements by fast protons, we have examined some of the light elements more carefully, using much thinner mica windows than we had previously employed on the high voltage tube. With the present arrangement, we can count particles which have passed through only 6 mm. air equivalent of absorber on their way from the target to the ionisation chamber. [中文](#)

In the case of lithium, we have found, in addition to the α -particle group of 8.4 cm. range, another group of particles of much shorter range. The number of these is about equal to that of the long range particles and their maximum range is about 2 cm. The ionisation

produced by them indicates that they are α -particles. It will be of interest to examine whether any γ -rays are emitted corresponding to the difference of the energies of the α -particles in the two groups, but on account of the smallness of the effect to be expected, a sensitive method will be necessary. [中文](#)

In the case of boron, the number of particles observed increases rapidly as the total absorption between the target and the ionisation chamber is reduced. The maximum range of these particles is about 3 cm. and in our earlier experiments we determined the number of particles only after passing through the equivalent of 2.9 cm. of air, so that we were very nearly at the end of the range. Decreasing the absorber to 6 mm. of air gives an enormous increase in the number of particles. In this way about twenty-five times as many particles have been obtained from boron as from lithium under the same conditions. We estimate that there is roughly one particle emitted per two million incident protons at 500 kilovolts. The ionisation produced by the particles suggests that they are α -particles, and the energy of the main group would support the assumption that a proton enters the B^{11} nucleus and the resulting nucleus breaks up into three α -particles. There also seem to be present a small number of particles with ranges up to about 5 cm. [中文](#)

(131, 23; 1933)

J. D. Cockcroft and E. T. S. Walton: Cavendish Laboratory, Cambridge, Dec. 22.

Reference:

1. *Proc. Roy. Soc., A*, **137**, 229 (1932).

快质子引起的轻元素衰变

约翰·道格拉斯·考克饶夫，欧内斯特·瓦耳顿

考克饶夫和瓦耳顿改进了对于高能质子与轻元素原子核之间相互作用的研究。在报告了人工引发的锂衰变之后，他们提高了探测仪器的灵敏度，并把研究范围扩展到了元素硼。他们发现硼被高能质子轰击后会产生大量的 α 粒子，说明发生了这样的核反应：硼11核在吸收了一个质子之后生成硼12，随后衰变成3个 α 粒子。 [英文](#)

在发表了关于快质子引起元素衰变的文章^[1]以后，我们对一些轻元素进行了更仔细的检查，我们所用的云母窗比以前在高压管上使用的要薄很多。采用目前的装置，我们能够对从靶出发穿越阻止能力仅相当于6 mm厚空气的吸收层到达电离室的粒子进行计数。 [英文](#)

我们在检测锂元素的实验中发现，除了一组射程为8.4 cm的 α 粒子以外，还有另一组射程更短的粒子。这些粒子与长射程粒子的数量大致相等，它们的最大射程约为2 cm。由它们产生的电离现象表明，它们也是 α 粒子。检验是否有与两组 α 粒子能量差相对应的 γ 射线产生对于我们来说是一件有趣的事，但考虑到该效应可能很微弱，所以需要一种很灵敏的方法。 [英文](#)

在对硼元素进行实验时，如果我们减少靶与电离室之间的总吸收，则观测到的粒子数就会迅速增加。这些粒子的最大射程约为3 cm，在早期的实验中，我们测定了穿越阻止能力相当于2.9 cm厚空气的粒子数，这非常接近于最大射程的终点。将吸收层厚度降至相当于6 mm空气时，得到的粒子数大幅增加。在相同条件下，由此方法从硼中得到的粒子约为从锂中得到的25倍。我们估计，当电压为500千伏时，大体上每200万个入射质子会激发出一个粒子。从这些粒子引起的电离来看它们就是 α 粒子，主要组 α 粒子的能量可以证明下面这个假设：一个质子进入

B^{11} 核，而生成的核又裂变为3个 α 粒子。似乎还存在少量射程高达5 cm 的粒子。 [英文](#)

（沈乃澂 翻译；江丕栋 审稿）

Energy of Cosmic Rays

E. Regener

Physicists had obtained increasingly accurate measurements of the ionisation created in the upper atmosphere by cosmic rays. Using this data, Erich Regener here estimates the energy flux of the cosmic rays impinging upon the Earth. He estimates that 108 pairs of ions are created per second in each square cm. As impinging cosmic rays need an energy of 32 electron-volts to trigger ionisation, this led to an estimate for the total energy flux of $5.2 \times 10^{-3} \text{ erg. cm.}^{-2} \text{ sec.}^{-1}$ As Regener notes, a body in thermal equilibrium under illumination from this flux would bear a temperature of 3.1 K, similar to Arthur Eddington's result for a body in equilibrium with the ordinary radiation coming from stars.

[中文](#)

IN Nature for September 3, 1932, p. 364, I published the curve of the intensity of cosmic radiation in the high atmosphere, deduced from measurements made with a self-registering electrometer. It was possible by extrapolation to find the intensity I_{∞} of radiation at its entrance in the atmosphere. The preliminary value given has now been corrected by the experimental determination of the factor which reduces the measurements with the ionisation chamber at 5 atmospheres to 1 atmosphere. Now the value I_{∞} is found corresponding to a production of 333 pairs of ions $\text{cm.}^{-3} \text{ sec.}^{-1}$ in air at 0° and 760 mm. mercury pressure. [中文](#)

The graphical integration of the curve, giving the ionisation as a function of the height, makes it possible to calculate the total number of ions, produced by total absorption of cosmic rays by a column of air of 1 sq. cm. section. The high value of 1.02×10^8 pairs of ions is found. Some time ago, Millikan and Cameron¹ made a similar calculation, which gave a value of only 1.28×10^7 pairs of ions, due to an insufficient knowledge of the intensity in the high atmosphere. Taking the energy required to produce a pair of ions in air² as 32 electron-volts the flux S of energy coming to the earth from the cosmic rays is found to be 5.2×10^{-3} erg. cm.⁻² sec.⁻¹. [中文](#)

From an astrophysical point of view, the great energy of cosmic rays is remarkable. A body which absorbs all the cosmic rays would be heated by them. Equilibrium will be attained when the absorbed flux S of cosmic rays is equal to the heat radiation σT^4 of that body. T works out as 3.1° Kelvin. The value is equal to the temperature (3.18°) which Eddington³ finds for a black body heated only by the heat and light radiation of stars. Eddington's calculation relates to a point in our local system of stars, but not in the neighbourhood of one of them. If at such a point the flux of energy of cosmic radiation is equal to that on the earth, the temperature of a black body, absorbing entirely the *two* radiations, rises only to 3.7° Kelvin, according to the T^4 law. But at a point in space among the spiral nebulae, the ordinary radiation is very small and causes only a very small rise of temperature. Supposing that cosmic rays originate in such intergalactic space, they would produce an elevation of temperature corresponding to the flux of cosmic rays. [中文](#)

A more detailed report will be published shortly in the *Zeitschrift für Physik*. [中文](#)

(131, 130; 1933)

References:

1. *Phys. Rev.*, **31**, 930 (1928).
2. Kulenkampff, H., *Phys. Z.*, **30**, 777 (1929).
3. *Internal Constitution of the Stars*, German edition, 468 (1928).

宇宙射线的能量

埃里克·雷格纳

物理学家们一直在对宇宙射线在高层大气中产生的电离效应进行测定，所得的结果越来越精确。埃里克·雷格纳利用这些数据估算了宇宙射线在撞击地球时的能量通量。他预计每秒在每平方厘米的面积上宇宙射线将有108个离子对通过。因为只有能量大于32 eV的宇宙射线才能产生电离效应，由此可以估算出宇宙射线的总能为 $5.2 \times 10^{-3} \text{ erg} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ 。雷格纳指出：一个处于热平衡状态中的物体在这么高能量射线流的照射下温度将升高3.1 K。这个值近似于阿瑟·爱丁顿从多数来自恒量的辐射对平衡态天体的影响中得到的结果。

[英文](#)

我在1932年9月3日《自然》杂志的第364页上公布了宇宙辐射在高层大气中的强度曲线，这条曲线是根据一台自动记录静电计的测量结果推演出来的。利用外推法可以得到宇宙射线在进入大气层时的辐射强度 I_{∞} 。现在原始数据已经可以用确定的实验因子进行修正，这个因子可以把电离室在5个大气压下测量的结果折合成1个大气压下的结果。目前得到的 I_{∞} 值相当于在0°C，760 mm汞柱空气中每秒每立方厘米产生333个离子对。

[英文](#)

对曲线进行图解积分，发现电离度是随高度变化的函数，这样就可以计算出在横截面积为1平方厘米的空气柱完全吸收宇宙射线后产生的离子对总数。我们发现这个值高达 1.02×10^8 对离子。早些时候，密立根和卡梅伦^[1]也进行过类似的计算，但由于他们对高层大气中的射线强度缺乏充分的认识，因而给出的数值仅为 1.28×10^7 对离子。如果在空气中产生一个离子对所需的能量^[2]为32 eV，那么宇宙射线带到地球上的能量通量 S 应该可以达到 $5.2 \times 10^{-3} \text{ erg} \cdot \text{cm}^{-2} \cdot \text{s}^{-1}$ 。

[英文](#)

从天体物理学的角度来看，宇宙射线的能量如此巨大是很不寻常的。一个吸收了全部宇宙射线的天体将因此而被加热。当天体所吸收的宇宙射线的总通量 S 等于其热辐射 σT^4 时，该天体就会达到平衡，这时计算出的温度值 T 为3.1 K，这与爱丁顿^[3]发现的只被恒星发出的光和热所加热的黑体所具有的温度值（3.18 K）相等。爱丁顿的计算仅关系到我们所处的局部恒星系统中的一个点，而不涉及其中某一个恒星的周边区域。如果在这样一个点上，宇宙辐射的能流与在地球上获得的能流相等，那么根据 T^4 定律，一个完全吸收了这两种辐射后的黑体的温度只会升至3.7 K。但对于处于旋涡状星云内的空间某一点来说，通常的辐射是非常小的，所以温度上升的幅度也微乎其微。假设宇宙射线起源于这样的星系际空间，它们将引发与宇宙射线通量相对应的升温现象。 [英文](#)

更详细的结果将在近期的《物理学杂志》上发表。 [英文](#)

（史春晖 翻译；马宇蓓 审稿）

Helium Liquefaction Plant at the Clarendon Laboratory, Oxford

F. A. Lindemann and T. C. Keeley

In the early 1930s, liquid helium had become precious to physicists studying the properties of matter at very low temperatures. Here the physicist Frederick Lindemann and colleagues at the University of Oxford announced the development of a new means for producing large quantities of liquid helium. Their technique used the liquefaction of hydrogen under an abrupt change in pressure to cool helium, and could produce large volumes of the liquid in continuous operation with relatively cheap apparatus. The liquid helium lasted in their laboratory for about one and one-half hours. This method and subsequent developments would enable the Soviet physicist Pyotr Kapitza to discover the phenomenon of superfluidity in liquid helium in 1938. [中文](#)

THE main properties of liquid helium have been familiar to men of science for a great many years. The only object therefore in liquefying it is in order to cool other substances the characteristics of which it is desired to study in the neighbourhood of the absolute zero. It has long been known that the heat capacity of solids becomes extremely small at low temperatures. Thus the latent heat of evaporation of 20 mgm. of liquid helium is sufficient to cool 60 gm. of copper from the temperature to be attained with liquid hydrogen boiling under a reduced pressure to the boiling point of helium. [中文](#)

It is easy to design apparatus so that the substances the properties of which at low temperatures are under investigation, are cooled to the temperature of the surrounding liquid or solid helium and maintained at this temperature with a minimum of waste. It seemed preferable, therefore, to instal a small inexpensive apparatus requiring comparatively little liquid hydrogen, which can therefore be operated frequently or duplicated at comparatively small cost, rather than to indulge in a plant designed to produce liquid helium in large quantities. In any event, the financial resources available would have imposed this choice, even had the alternative procedure been considered desirable. 中文

The apparatus which has been installed at Oxford is of a type developed by Prof. Simon and Dr. Mendelssohn in Berlin and Breslau. Two concentric cylinders capable of withstanding a pressure of some 150 atmospheres surround the space in which the substance under investigation is placed. Helium under a pressure of about 100 atmospheres is introduced into the space between the cylinders. The upper part of the annular space between the cylinders is separated from the lower, in which the helium is compressed, by a metal sheet, thus forming a small metal container which is joined by a spiral of thin copper tubing to a source of pure hydrogen. The whole is held in position on a German silver tube in the centre of a larger metal vessel containing hydrogen or helium gas at low pressure which can be evacuated by means of a mercury vapour pump. This outer vessel together with the copper spirals through which the hydrogen and helium are introduced is immersed in a Dewar flask containing liquid hydrogen. 中文

When temperature equilibrium has been attained, hydrogen is introduced into the top vessel under a pressure of two or three atmospheres. Passing through the copper spirals, this liquefies owing to the excess pressure and runs down into the metal container over the

double-walled helium cylinder. A tap to the mercury vapour pump is now turned on and a high vacuum produced in the metal box, so that the helium container with its superposed pot of liquid hydrogen is thermally insulated save for the necessary connecting tubes. 中文

The yield of liquid helium is improved if the compressed helium is further cooled by boiling the hydrogen in the inner container under reduced pressure. If the helium is now allowed to expand, about half of it liquefies and the central space with the experimental substances it contains is cooled to the temperature of the surrounding helium. By evacuating the space above the liquid, that is, causing it to boil under reduced pressure, one can, of course, reduce the temperature to within one or two degrees of the absolute zero. 中文

In the apparatus used at Oxford the helium lasts for about an hour and a half. If the experiment is not finished in this time, one can repeat the process in a few minutes at very small cost in liquid hydrogen. The helium expands into a rubber bag and is recompressed into a cylinder so that very little gas is lost. The temperature during the experiment can be observed on a large-scale manometer connected through a fine tube to a small vessel containing helium in the liquefaction space. The apparatus cost approximately £30. Since there is no need to recompress the helium rapidly, a small cheap compressor is sufficient.

中文

The liquid hydrogen required is produced in a plant of the standard pattern designed in the Physico-Chemical Institute in Berlin which has been in use at Oxford for some years now without giving any trouble. Impurities in the hydrogen are condensed by a preliminary expansion and continuously removed by a slow stream of hydrogen. With a compressor capable of dealing with ten cubic metres of free gas an hour and an expenditure of approximately 1.4 litres of liquid nitrogen per litre of liquid hydrogen, this plant produces some $2\frac{1}{2}$ litres of liquid hydrogen per hour. Liquefier and compressor together cost

approximately £ 350. [中文](#)

The liquid hydrogen is stored in pyrex Dewar flasks silvered and exhausted in the laboratory. As their efficiency equalled that claimed for the more complicated double vessels developed by Prof. Kapitza, they have been retained. [中文](#)

If low temperature work expands and a large number of experiments are in hand simultaneously, it may be necessary to consider the use of the continuous Linde process of liquefaction. In view of the cost of the gas and the precautions necessary for its recovery, its distribution involves considerable inconvenience, which for the time being are scarcely worth facing. The mere liquefaction, of course, offers no difficulties and there is little doubt that the Berlin type of apparatus, which is already in use in many laboratories, will prove as serviceable and efficient as the hydrogen liquefier, should it ever be necessary to change over to this system. [中文](#)

Finally, a word of thanks is due to Dr. Mendelssohn, who kindly brought the liquefier over from Breslau and placed all his knowledge and experience unreservedly at the disposal of the department. But for this, it would scarcely have been possible to obtain, without hitch or trouble, liquid helium within one week of the arrival of the apparatus in Oxford. [中文](#)

(131, 191-192; 1933)

牛津大学克拉伦登实验室的氦液化车间

弗雷德里克·林德曼，托马斯·基利

在20世纪30年代早期，液氦对于研究很低温度下物质性质的物理学家来说是十分珍贵的。在本文中，牛津大学的物理学家弗雷德里克·林德曼及其同事宣布研发出了一种能生产大量液氦的新方法。他们采用突然改变液态氦压力的方式来冷却氦，可以用这种较便宜的装置连续地得到大量的液氦。他们的实验室持续生产了1.5个小时的液氦。正是这一方法及接下来的一些发展使苏联物理学家彼得·卡皮查得以在1938年发现液氦中的超流性现象。 [英文](#)

多年以来，液氦的主要性质就已为科学界的人士所熟知。所以人们把氦液化的唯一目的，是想用它来冷却其他物质以便研究它们在绝对零度附近的性质。长期以来人们就知道，固体的热容量在低温时会变得非常小。因此，蒸发20毫克液氦吸收的潜热足以使60克铜的温度从减压液态氦沸腾的温度降低到液氦沸点的温度。 [英文](#)

为了研究低温下物质的性质，很容易设计一个实验装置把物质冷却到与其周围的液氦或固氦温度相同的温度，并以最小的损失使物质保持在这个温度。不过，我们更喜欢对液氦需求相对较少的小型廉价装置，而不是一个能大量生产液氦的工厂，因为选择小型设备可以降低经常运转或复制它的成本。无论如何，由于财力所限，即便是还有其他令人满意的方式可供选择，也只能选择这种装置。 [英文](#)

安装在牛津大学的设备是由柏林的西蒙教授和布雷斯劳的门德尔松博士研制的。要研究的物质被装在由两个可承受150个大气压的同心圆桶围绕的空间中。在两个圆桶之间的空间注入压强约为100个大气压的

氢。圆桶之间的环状区域被一金属板分隔成上下两部分，上部分形成了一个小的金属容器，并通过一根螺线型的细铜管与纯氢的供应源相连，氢在下半部分被压缩。整个装置用一根德银管保持在一个更大的金属容器的中心，该容器中充有低压的氢气或氦气，可用汞蒸汽泵抽成真空。最外面的容器与输送氢和氦的铜螺线管一起浸没在一个含有液态氢的杜瓦瓶内。

[英文](#)

当温度达到平衡时，压强为2或3个大气压的氢被注入到上部的容器中。氢气通过铜螺线管时由于所受压力过大而被液化，随后流入到在双壁氢圆桶上的金属容器中。这时打开连接汞蒸汽泵的阀门，金属容器内就会产生高真空，从而除了所需的连接管以外，氢容器与在它上面的液氢罐都与外界热绝缘。

[英文](#)

如果通过减压使内层容器中的氢达到沸点以进一步冷却压缩状态下的氢，就可以提高液氢的产量。现在允许氦气膨胀，约一半的氦会被液化，放有实验物质的中间区域也会被冷却到与周围氦一样的温度。如果在液体上方抽真空，也就是让液体在减压的情况下沸腾，我们就可以把温度降低到距绝对零度一两度的范围之内。

[英文](#)

牛津大学的设备能使液氢持续运转约1.5小时。如果在1.5个小时之内实验还没有做完，我们可在几分钟之内就开始重复上述过程，这只需消耗一些很便宜的液氢而已。氦气膨胀进入一个橡皮袋，然后被压缩到钢瓶内，所以丢失的气体很少。我们可以通过一个大量程的压力计观察实验时的温度，这个压力计通过一根细管子连接到液化区内的含氦气小容器上。这个设备的造价约为30英镑。因为不需要快速压缩氦气，所以使用一台小型廉价的压缩机就够了。

[英文](#)

所需的液氢是用柏林物理化学研究所设计的标准设备生产的，目前这个设备已经在牛津大学无故障地运转了好几年了。氢气中的杂质先经过一次预膨胀使之凝聚，然后通过氢的低速流动继续去除杂质。使用的是每小时能处理10立方米自由气体的压缩机，每升液氢需要消耗约1.4升液氮，这个车间每小时可生产约2.5升的液氢。液化器和压缩机的总造价约为350英镑。

[英文](#)

液氢被储存在镀银的派热克斯玻璃杜瓦瓶中并在实验室中耗尽掉。

由于派热克斯玻璃杜瓦瓶与卡皮查教授研制的较复杂的双容器杜瓦具有相同的功效，所以我们一直在使用这些杜瓦瓶。 [英文](#)

如果低温工作扩展了，需要在低温下同时进行多项实验，恐怕就要考虑采用连续的林德液化过程了。考虑到气体很昂贵，以及必须仔细地回收气体，使用这一方法还有相当大的不便，所以目前还不太值得考虑。如果必须改为使用这种系统的话，仅从实现液化而言，柏林型装置当然是没有任何困难的，毫无疑问，它将被证明与氢液化器一样好用而高效，而且很多的实验室已在使用它。 [英文](#)

最后，我要对门德尔松博士表示感谢，他慷慨地从布雷斯劳带来液化器并把自己所有的知识和经验毫无保留地贡献给这个系自由处理。否则，我们几乎不可能在设备到达牛津大学的一周之内，没有遇到任何麻烦就顺利地制备出液氦来。 [英文](#)

（沈乃澍 翻译；陶宏杰 审稿）

Recent Researches on the Transmutation of the Elements*

E. Rutherford

Ernest Rutherford here offers a snapshot of the rapidly advancing field of nuclear transmutation. It had been established that many atoms can be changed from one element to another by adding or subtracting any of the various particles believed to inhabit the nucleus. But so far no such reactions had been observed with heavy elements such as thallium, lead, bismuth or uranium. This might change, Rutherford says, as physicists around the world—notably Ernest Lawrence at the University of California—were developing accelerating devices of considerably higher energy. None, however, compared to the energies of cosmic rays, with which several experiments had recently found tentative evidence for a positively charged electron—later identified as the positron. 中文

IT is now well established that the change of one atom into another can only be effected by the addition or subtraction of one of the constituent particles of the atomic nucleus, for example, an electron, proton, neutron or α -particle. Such a transformation was first accomplished in 1919 for the element nitrogen by bombarding it with swift α -particles from radioactive substances. About one α -particle in 100,000 comes so close to the nucleus that it enters and is captured by it. This violent disturbance results in the expulsion of a proton with

high speed, and the formation of a new nucleus of mass 17. A number of light elements can be transformed by α -particle bombardment in a similar way, and in most cases a proton is ejected. [中文](#)

A new and strange type of transformation was discovered last year by Chadwick: when α -particles bombard the metal beryllium, uncharged particles of mass 1 called neutrons are expelled. These neutrons, which have remarkable powers of penetrating matter, are themselves very efficient agents for the transformation of atoms. Feather has shown that both nitrogen and oxygen are transformed by the capture of neutrons, with the expulsion of a fast α -particle. The types of transformations produced by the neutron are thus very different from those observed with the α -particle. The capture of an α -particle in general leads to the building up of a new nucleus three units heavier than before, while the capture of a neutron leads to the formation of a nucleus three units lighter. [中文](#)

During the past year, Cockcroft and Walton at Cambridge made the important discovery that comparatively low-speed protons are very effective in causing the transformation of a number of elements. The protons are generated in large numbers by an electric discharge through hydrogen, and then speeded up by passing through an evacuated space to which a high potential of the order of 600,000 volts is applied. Under these conditions the protons acquire high speeds comparable with that of the α -particle from radium. When a stream of these swift protons corresponding to a micro-ampere falls on the element lithium, a large number of α -particles are emitted of energy comparable with that of the swiftest α -particle from radium. It seems that about one in 100 million of the protons enters a lithium nucleus of mass 7, and the resulting nucleus of mass 8 splits up into two α -particles, each of mass 4. Cockcroft and Walton have later found that the α -particles emitted consist of two groups differing widely in speed. [中文](#)

This transformation of lithium can be produced at surprisingly low voltages. With strong proton streams, the emission of α -particles can be observed for 30,000 volts; the number of particles increases rapidly with the voltage, and the variation has been examined by different observers over a very wide range, from 30,000 to 1.5 million volts.

[中文](#)

Protons are also remarkably effective in disintegrating the light element boron, and again α -particles are emitted. It is possible in this case that the boron nucleus of mass 11, after capturing a proton, breaks up into three α -particles. The radiation observed is complex, and has not yet been analysed in detail. A number of other elements have been found to be transformed, apparently in all cases with the emission of α -particles.

[中文](#)

In a special form of accelerating tube devised by Oliphant in the Cavendish Laboratory, a narrow, intense proton stream can be generated at voltages up to 200,000 volts. The protons, after being bent by a magnetic field, bombard a target of about one square centimetre in area. By special arrangements, it has been found possible to obtain in the detecting chamber at least a thousand times the number of particles observed by Cockcroft and Walton at the same voltage. By this method it is easy to observe the particles from very thin films of lithium and boron at comparatively low voltages, while the variation of number with voltage has been measured. For example, a number of α -particles are emitted from lithium with voltages so low as 30,000 volts. α -Particles from boron have been observed at 60,000 volts, but the number increases much more rapidly with voltage than in the case of lithium.

[中文](#)

Special experiments have been made to test by this sensitive method whether the heavy elements thallium, lead, bismuth and uranium show any evidences of transformation for 200,000 volt protons, but no sign of emission of α -particles has been observed for these elements.

At first, marked effects were observed, but these were ultimately traced to a minute contamination by boron, probably originating in the discharge tube. It seems not unlikely that the effect observed for uranium and lead in the original experiments of Cockcroft and Walton may have been due to an unsuspected contamination by a minute trace of the very active element boron. [中文](#)

During the last few years, much energy has been devoted throughout the world to developing methods of obtaining streams of very swift charged particles with which to bombard matter and effect its transmutation. In the apparatus of Cockcroft and Walton at Cambridge already referred to, a steady potential of 800,000 volts can be reached. A new and simple type of electrostatic generator has been designed by Van der Graaf and Atta in the Massachusetts Institute of Technology, with which they have obtained a steady potential of 1.5 million volts, and a larger apparatus is under construction with which they hope to obtain a potential of 15 million volts to apply to a large vacuum tube. Brasch and Lange have applied high momentary voltages to a discharge tube by using an impulse generator. [中文](#)

A new and ingenious method of multiple acceleration has been devised by Lawrence of the University of California with which he has already obtained protons of energy 1.5 million volts by using a potential less than 10,000 volts. The transformation of lithium has been examined at this high energy using a proton current of about a thousandth of a micro-ampere. It is hoped to develop this method so as to obtain protons of energy as high as 10 million volts or more.

[中文](#)

Even if these new projects prove successful, the speeds of particles produced by their aid are much smaller than those observed for the very penetrating radiation in our atmosphere, where electrons and protons of energy from 200 million to 2,000 million volts are present. From the experiments of Anderson in Pasadena and Blackett and

Occhialini in Cambridge, it seems certain that these very swift particles are very efficient in causing the transformation of nuclei, probably in novel ways. Strong evidence has been obtained of the production of a new type of positively charged particle which has a mass small compared with that of the proton. This may prove to be the positive electron, the counterpart of the well-known negative electron of light mass. [中文](#)

(131, 388-389; 1933)

* Substance of the Friday evening discourse delivered at the Royal Institution on March 10.

关于元素嬗变的最新研究*

欧内斯特·卢瑟福

欧内斯特·卢瑟福在这篇文章中发表了对快速发展的核嬗变领域的简评。已经确认许多原子都可以通过增加或减少核中的任意粒子使自己从一种元素转变成另一种元素。但迄今为止人们在像铀、铅、铋和铀这样的重元素中还没有观察到这种反应。卢瑟福说：这个结论可能会有所改变，因为全世界的物理学家，尤其是美国加州大学的欧内斯特·劳伦斯，正在研制能量更高的加速器。不过所得到的能量无法和宇宙射线的能量相比，最近一些与宇宙射线相关的实验显示可能存在一种带正电的电子——后来被人们确定为正电子。

英文

目前我们完全可以认为：仅仅通过增加或减少原子核的一个组成粒子如电子、质子、中子或 α 粒子就可以使一种原子变为另一种原子。这种嬗变是1919年用放射性物质发射的快速 α 粒子轰击氮元素时首次完成的。有约十万分之一的 α 粒子非常接近原子核以至于进入其中而被其俘获。这种强力扰动除了导致放出高速的质子，还形成了质量为17的新原子核。用类似的方法以 α 粒子轰击可以嬗变一些轻元素，而且在大多数情况下，会放出一个质子。

英文

去年，查德威克发现了一类新奇的嬗变：当 α 粒子轰击金属铍时，放射出质量为1、被称为中子的不带电的粒子。中子对于物质有极强的穿透性，是产生原子嬗变非常有效的工具。费瑟指出，氮和氧都可以通过中子俘获发生嬗变，并放出一个快速 α 粒子。由中子引发的这类嬗变与那些由 α 粒子引发的嬗变有很大的差别。通常， α 粒子俘获生成的新原子核比之前的质量重三个原子质量单位，而中子俘获产生的原子核要比之前轻三个原子质量单位。

英文

去年，剑桥大学的考克饶夫和瓦耳顿作出了重要的发现，相对低速的质子在引发许多元素的嬗变中都是非常有效的。质子在氢原子放电的过程中大量产生，随后在加有600,000伏高电压的真空中被加速。在这样的条件下，质子获得了与从镭中放射出的 α 粒子相当的高速度。当这些相应于微安级电流的快速质子束流轰击元素锂时，发射出大量的 α 粒子，其能量与从镭中放射出的最快速的 α 粒子的能量相当。大约有亿分之一的质子进入质量为7的锂原子核，产生质量为8的原子核，该原子核又分裂为两个质量为4的 α 粒子。考克饶夫和瓦耳顿后来发现，所发射的 α 粒子由速度相差很大的两群组成。

[英文](#)

锂的嬗变可以在特别低的电压下产生。用强的质子流，可以观测到在30,000伏时放射出 α 粒子；粒子数目随着电压的加大而快速增加，在从30,000伏到1.5百万伏这个非常宽的范围内，不同的观测者都检测到了这种变化。

[英文](#)

质子在蜕变轻元素硼时也是非常有效的，且会再次放出 α 粒子。在这种情况下，质量为11的硼原子核在俘获一个质子后破裂为三个 α 粒子是可能的。所观测到的辐射很复杂，详细的分析还未完成。许多其他的元素也已被发现可以发生嬗变，当然，在所有的情况下都会放出 α 粒子。

[英文](#)

在由卡文迪什实验室的奥利芬特发明的特殊形式的加速管中，细而强的质子束流可以在高至200,000伏的电压下产生。经过磁场偏转的质子流轰击面积约为1平方厘米的靶。通过特殊的装置，在检测室中可以得到的粒子数比考克饶夫和瓦耳顿在相同电压下观测到的粒子数至少大几千倍。用这种方法很容易观测到在相当低电压下从非常薄的锂和硼薄膜中放射出的粒子，还测量了粒子数随电压的变化。例如，在电压低至30,000伏时从锂中可以放出许多 α 粒子。在电压为60,000伏时观测到了从硼放出的 α 粒子，但与锂的情况相比， α 粒子的数量随电压增加得更快。

[英文](#)

通过这种灵敏的方法人们已经进行了特殊的实验用以检验重元素铀、钍、镭和钋对200,000伏的质子是否显示任何嬗变的迹象，但并未观测到这些元素有发射 α 粒子的迹象。最初，观测到了明显的效应，但

最终追查到这些效应是由硼的微量污染引起的，它可能来自于放电管。这似乎有可能就是考克饶夫和瓦耳顿在最初的铀和铅的实验中观测到的效应，它们可能是由微量非常活泼的元素硼的未知污染产生的。 [英文](#)

在最近几年间，全世界都在投入大量精力用以发展获得快速带电粒子流的方法，以便利用这些带电粒子来轰击物质并使其发生嬗变。已经提到剑桥大学的考克饶夫和瓦耳顿的装置可以达到800,000伏的稳定电压。麻省理工学院的范德格拉夫和阿塔设计出了一台简单的新型静电加速器，他们用此得到了1.5百万伏的稳定电压。他们还在构建更大的装置，以期获得15百万伏的电压并将之应用到大的真空钢筒内。布拉什和兰格已将瞬时高电压通过脉冲发生器加到放电管上。 [英文](#)

加州大学的劳伦斯发明了一种新的直接多次加速的巧妙方法，他用小于10,000伏的电压得到的质子能量为1.5百万伏。在使用约千分之一微安的质子流时，锂在这种高能下发生的嬗变得到了检验。这类方法被寄予厚望，因为它可能获得高达10百万伏甚至更高能量的质子。 [英文](#)

即使这些新方案被证明是成功的，由它们产生的粒子速度仍远小于我们在大气层中观测到的穿透力很强的辐射，大气中电子和质子的能量在200百万伏到2,000百万伏之间。帕萨迪纳的安德森及剑桥大学的布莱克特和奥基亚利尼的实验似乎表明，这些非常快的粒子在引起原子核的嬗变中是很有效的，也许是新方式的嬗变。强有力的证据表明产生了一种比质子质量小且带正电的新型粒子。它可能被证明是正电子，即为人们所熟知的轻质量带负电荷的电子的反粒子。 [英文](#)

（沈乃澂 翻译；张焕乔 审稿）

* 本文取自作者于3月10日在英国皇家研究院所作的周五晚间演讲。

Light and Life*

N. Bohr

This is an address given by Niels Bohr at the International Congress on Light Therapy in Copenhagen. Bohr had been invited to discuss the beneficial effects of light in curing diseases, but he spoke instead on the potential implications of the new quantum understanding of light for the science of living organisms. Despite the inadequacy of the wave picture for detailing the behaviour of light quanta, says Bohr, there could be no question of replacing it with a purely quantum-mechanical “particle” picture. He points out that any attempt to measure the trajectories of photons precisely inevitably destroys the phenomenon of wave interference. Such problems, he suggests, compel abandonment of a complete causal description of light phenomena.

In the second part of his address, Bohr argues that the implications of quantum theory stretch well beyond atomic physics. The assimilation of carbon by plants surely involved the quantum nature of interactions between light and matter, and the ability of the human eye to detect only a few photons suggests that its design probes the quantum limits of optics. Bohr suggests an analogy between uncertainty in the physical and biological worlds. Attempts to study organisms closely may ultimately interfere with their vital organs, just as physicists must disturb particles in order to study them. Perhaps life and consciousness may never be explained, but

must be accepted a priori much as the quantum action is axiomatic in physics. [中文](#)

Part I

AS a physicist whose studies are limited to the properties of inanimate bodies, it is not without hesitation that I have accepted the kind invitation to address this assembly of scientific men met together to forward our knowledge of the beneficial effects of light in the cure of diseases. Unable as I am to contribute to this beautiful branch of science that is so important for the welfare of mankind, I could at most comment on the purely inorganic light phenomena which have exerted a special attraction for physicists throughout the ages, not least owing to the fact that light is our principal tool of observation. I have thought, however, that on this occasion it might perhaps be of interest, in connexion with such comments, to enter on the problem of what significance the results reached in the limited domain of physics may have for our views on the position of living organisms in the realm of natural science. [中文](#)

Notwithstanding the subtle character of the riddles of life, this problem has presented itself at every stage of science, since any scientific explanation necessarily must consist in reducing the description of more complex phenomena to that of simpler ones. At the moment, however, the unsuspected discovery of an essential limitation of the mechanical description of natural phenomena, revealed by the recent development of the atomic theory, has lent new interest to the old problem. This limitation was, in fact, first recognised through a thorough study of the interaction between light and material bodies, which disclosed features that cannot be brought into conformity with the demands hitherto made to a physical explanation. As I shall endeavour to show, the efforts of physicists to master this situation resemble in some way the attitude which

biologists more or less intuitively have taken towards the aspects of life. Still, I wish to stress at once that it is only in this formal respect that light, which is perhaps the least complex of all physical phenomena, exhibits an analogy to life, the diversity of which is far beyond the grasp of scientific analysis. [中文](#)

From a physical point of view, light may be defined as the transmission of energy between material bodies at a distance. As is well known, such an energy transfer finds a simple explanation in the electromagnetic theory, which may be regarded as a direct extension of classical mechanics compromising between action at a distance and contact forces. According to this theory, light is described as coupled electric and magnetic oscillations which differ from the ordinary electromagnetic waves used in radio transmission only by their greater frequency of vibration and smaller wave-length. In fact, the practically rectilinear propagation of light, on which rests our location of bodies by direct vision or by suitable optical instruments, depends entirely on the smallness of the wave-length compared with the dimensions of the bodies concerned, and of the instruments. [中文](#)

The idea of the wave nature of light, however, not only forms the basis for our explanation of the colour phenomena, which in spectroscopy have yielded such important information of the inner constitution of matter, but is also of essential importance for every detailed analysis of optical phenomena. As a typical example, I need only mention the interference patterns which appear when light from one source can travel to a screen along two different paths. In such a case, we find that the effects which would be produced by the separate light beams are strengthened at those points on the screen where the phases of the two wave trains coincide, that is, where the electric and magnetic oscillations in the two beams have the same directions, while the effects are weakened and may even disappear at points where these oscillations have opposite directions, and where

the two wave trains are said to be out of phase with one another. These interference patterns have made possible such a thorough test of the wave nature of the propagation of light, that this conception can no longer be considered as a hypothesis in the usual sense of this word, but may rather be regarded as an indispensable element in the description of the phenomena observed. 中文

As is well known, the problem of the nature of light has, nevertheless, been subjected to renewed discussion in recent years, as a result of the discovery of a peculiar atomistic feature in the energy transmission which is quite unintelligible from the point of view of the electromagnetic theory. It has turned out, in fact, that all effects of light may be traced down to individual processes, in each of which a so-called light quantum is exchanged, the energy of which is equal to the product of the frequency of the electromagnetic oscillations and the universal quantum of action, or Planck's constant. The striking contrast between this atomicity of the light phenomena and the continuity of the energy transfer according to the electromagnetic theory places us before a dilemma of a character hitherto unknown in physics. For, in spite of the obvious insufficiency of the wave picture, there can be no question of replacing it by any other picture of light propagation depending on ordinary mechanical ideas. 中文

Especially, it should be emphasised that the introduction of the concept of light quanta in no way means a return to the old idea of material particles with well-defined paths as the carriers of the light energy. In fact, it is characteristic of all the phenomena of light, in the description of which the wave picture plays an essential rôle, that any attempt to trace the paths of the individual light quanta would disturb the very phenomenon under investigation; just as an interference pattern would completely disappear, if, in order to make sure that the light energy travelled only along one of the two paths between the source and the screen, we should introduce a non-transparent body

into one of the paths. The spatial continuity of light propagation, on one hand, and the atomicity of the light effects, on the other hand, must, therefore, be considered as complementary aspects of one reality, in the sense that each expresses an important feature of the phenomena of light, which, although irreconcilable from a mechanical point of view, can never be in direct contradiction, since a closer analysis of one or the other feature in mechanical terms would demand mutually exclusive experimental arrangements. [中文](#)

At the same time, this very situation forces us to renounce a complete causal description of the phenomena of light and to be content with probability calculations, based on the fact that the electromagnetic description of energy transfer by light remains valid in a statistical sense. Such calculations form a typical application of the so-called correspondence argument, which expresses our endeavour, by means of a suitably limited use of mechanical and electromagnetic concepts, to obtain a statistical description of the atomic phenomena that appears as a rational generalisation of the classical physical theories, in spite of the fact that the quantum of action from their point of view must be considered as an irrationality. [中文](#)

At first sight, this situation might appear very deplorable; but, as has often happened in the history of science, when new discoveries have revealed an essential limitation of ideas the universal applicability of which had never been disputed, we have been rewarded by getting a wider view and a greater power of correlating phenomena which before might even have appeared as contradictory. Thus, the strange limitation of classical mechanics, symbolised by the quantum of action, has given us a clue to an understanding of the peculiar stability of atoms which forms a basic assumption in the mechanical description of any natural phenomenon. The recognition that the indivisibility of atoms cannot be understood in mechanical terms has always characterised the atomic theory, to be sure; and this fact is not

essentially altered, although the development of physics has replaced the indivisible atoms by the elementary electric particles, electrons and atomic nuclei, of which the atoms of the elements as well as the molecules of the chemical compounds are now supposed to consist.

中文

However, it is not to the question of the intrinsic stability of these elementary particles that I am here referring, but to the problem of the required stability of the structures composed of them. As a matter of fact, the very possibility of a continuous transfer of energy, which marks both the classical mechanics and the electromagnetic theory, cannot be reconciled with an explanation of the characteristic properties of the elements and the compounds. Indeed, the classical theories do not even allow us to explain the existence of rigid bodies, on which all measurements made for the purpose of ordering phenomena in space and time ultimately rest. However, in connexion with the discovery of the quantum of action, we have learned that every change in the energy of an atom or a molecule must be considered as an individual process, in which the atom goes over from one of its so-called stationary states to another. Moreover, since just one light quantum appears or disappears in a transition process by which light is emitted or absorbed by an atom, we are able by means of spectroscopic observations to measure directly the energy of each of these stationary states. The information thus derived has been most instructively corroborated also by the study of the energy exchanges which take place in atomic collisions and in chemical reactions. 中

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In recent years, a remarkable development of the atomic theory has taken place, which has given us such adequate methods of computing the energy values for the stationary states, and also the probabilities of the transition processes, that our account, on the lines of the correspondence argument, of the properties of atoms as regards

completeness and self-consistency scarcely falls short of the explanation of astronomical observations offered by Newtonian mechanics. Although the rational treatment of the problems of atomic mechanics was possible only after the introduction of new symbolic artifices, the lesson taught us by the analysis of the phenomena of light is still of decisive importance for our estimation of this development. Thus, an unambiguous use of the concept of a stationary state is complementary to a mechanical analysis of intra-atomic motions; in a similar way the idea of light quanta is complementary to the electromagnetic theory of radiation. Indeed, any attempt to trace the detailed course of the transition process would involve an uncontrollable exchange of energy between the atom and the measuring instruments, which would completely disturb the very energy transfer we set out to investigate. [中文](#)

A causal description in the classical sense is possible only in such cases where the action involved is large compared with the quantum of action, and where, therefore, a subdivision of the phenomena is possible without disturbing them essentially. If this condition is not fulfilled, we cannot disregard the interaction between the measuring instruments and the object under investigation, and we must especially take into consideration that the various measurements required for a complete mechanical description may only be made with mutually exclusive experimental arrangements. In order fully to understand this fundamental limitation of the mechanical analysis of atomic phenomena, one must realise clearly, further, that in a physical measurement it is never possible to take the interaction between object and measuring instruments directly into account. For the instruments cannot be included in the investigation while they are serving as means of observation. As the concept of general relativity expresses the essential dependence of physical phenomena on the frame of reference used for their co-ordination in space and time, so does the notion of complementarity serve to symbolise the

fundamental limitation, met with in atomic physics, of our ingrained idea of phenomena as existing independently of the means by which they are observed. [中文](#)

(131, 421-423; 1933)

Part II

This revision of the foundations of mechanics, extending to the very question of what may be meant by a physical explanation, has not only been essential, however, for the elucidation of the situation in atomic theory, but has also created a new background for the discussion of the relation of physics to the problems of biology. This must certainly not be taken to mean that in actual atomic phenomena we meet with features which show a closer resemblance to the properties of living organisms than do ordinary physical effects. At first sight, the essentially statistical character of atomic mechanics might even seem difficult to reconcile with an explanation of the marvellously refined organisation, which every living being possesses, and which permits it to implant all the characteristics of its species into a minute germ cell. [中文](#)

We must not forget, however, that the regularities peculiar to atomic processes, which are foreign to causal mechanics and find their place only within the complementary mode of description, are at least as important for the account of the behaviour of living organisms as for the explanation of the specific properties of inorganic matter. Thus, in the carbon assimilation of plants, on which depends largely also the nourishment of animals, we are dealing with a phenomenon for the understanding of which the individuality of photo-chemical processes must undoubtedly be taken into consideration. Likewise, the peculiar stability of atomic structures is clearly exhibited in the characteristic properties of such highly complicated chemical compounds as chlorophyll or haemoglobin, which play fundamental rôles in plant

assimilation and animal respiration.

[中文](#)

However, analogies from chemical experience will not, of course, any more than the ancient comparison of life with fire, give a better explanation of living organisms than will the resemblance, often mentioned, between living organisms and such purely mechanical contrivances as clockworks. An understanding of the essential characteristics of living beings must be sought, no doubt, in their peculiar organisation, in which features that may be analysed by the usual mechanics are interwoven with typically atomistic traits in a manner having no counterpart in inorganic matter. [中文](#)

An instructive illustration of the refinement to which this organisation is developed has been obtained through the study of the construction and function of the eye, for which the simplicity of the phenomena of light has again been most helpful. I need not go into details here, but shall just recall how ophthalmology has revealed to us the ideal properties of the human eye as an optical instrument. Indeed, the dimensions of the interference patterns, which on account of the wave nature of light set the limit for the image formation in the eye, practically coincide with the size of such partitions of the retina which have separate nervous connexion with the brain. Moreover, since the absorption of a few light quanta, or perhaps of only a single quantum, on such a retinal partition is sufficient to produce a sight impression, the sensitiveness of the eye may even be said to have reached the limit imposed by the atomic character of the light effects. In both respects, the efficiency of the eye is the same as that of a good telescope or microscope, connected with a suitable amplifier so as to make the individual processes observable. It is true that it is possible by such instruments essentially to increase our powers of observation, but, owing to the very limits imposed by the properties of light, no instrument is imaginable which is more efficient for its purpose than the eye. Now, this ideal refinement of the eye, fully recognised only

through the recent development of physics, suggests that other organs also, whether they serve for the reception of information from the surroundings or for the reaction to sense impressions, will exhibit a similar adaptation to their purpose, and that also in these cases the feature of individuality symbolised by the quantum of action, together with some amplifying mechanism, is of decisive importance. That it has not yet been possible to trace the limit in organs other than the eye, depends solely upon the simplicity of light as compared with other physical phenomena. [中文](#)

The recognition of the essential importance of fundamentally atomistic features in the functions of living organisms is by no means sufficient, however, for a comprehensive explanation of biological phenomena. The question at issue, therefore, is whether some fundamental traits are still missing in the analysis of natural phenomena, before we can reach an understanding of life on the basis of physical experience. Quite apart from the practically inexhaustible abundance of biological phenomena, an answer to this question can scarcely be given without an examination of what we may understand by a physical explanation, still more penetrating than that to which the discovery of the quantum of action has already forced us. On one hand, the wonderful features which are constantly revealed in physiological investigations and differ so strikingly from what is known of inorganic matter, have led many biologists to doubt that a real understanding of the nature of life is possible on a purely physical basis. On the other hand, this view, often known as vitalism, scarcely finds its proper expression in the old supposition that a peculiar vital force, quite unknown to physics, governs all organic life. I think we all agree with Newton that the real basis of science is the conviction that Nature under the same conditions will always exhibit the same regularities. Therefore, if we were able to push the analysis of the mechanism of living organisms as far as that of atomic phenomena, we should scarcely expect to find any features differing from the

properties of inorganic matter.

[中文](#)

With this dilemma before us, we must keep in mind, however, that the conditions holding for biological and physical researches are not directly comparable, since the necessity of keeping the object of investigation alive imposes a restriction on the former, which finds no counterpart in the latter. Thus, we should doubtless kill an animal if we tried to carry the investigation of its organs so far that we could describe the rôle played by single atoms in vital functions. In every experiment on living organisms, there must remain an uncertainty as regards the physical conditions to which they are subjected, and the idea suggests itself that the minimal freedom we must allow the organism in this respect is just large enough to permit it, so to say, to hide its ultimate secrets from us. On this view, the existence of life must be considered as an elementary fact that cannot be explained, but must be taken as a starting point in biology, in a similar way as the quantum of action, which appears as an irrational element from the point of view of classical mechanical physics, taken together with the existence of the elementary particles, forms the foundation of atomic physics. The asserted impossibility of a physical or chemical explanation of the function peculiar to life would in this sense be analogous to the insufficiency of the mechanical analysis for the understanding of the stability of atoms.

[中文](#)

In tracing this analogy further, however, we must not forget that the problems present essentially different aspects in physics and in biology. While in atomic physics we are primarily interested in the properties of matter in its simplest forms, the complexity of the material systems with which we are concerned in biology is of fundamental significance, since even the most primitive organisms contain a large number of atoms. It is true that the wide field of application of classical mechanics, including our account of the measuring instruments used in atomic physics, depends on the

possibility of disregarding largely the complementarity, entailed by the quantum of action, in the description of bodies containing very many atoms. It is typical of biological researches, however, that the external conditions to which any separate atom is subjected can never be controlled in the same manner as in the fundamental experiments of atomic physics. In fact, we cannot even tell which atoms really belong to a living organism, since any vital function is accompanied by an exchange of material, whereby atoms are constantly taken up into and expelled from the organisation which constitutes the living being. [中文](#)

This fundamental difference between physical and biological investigations implies that no well-defined limit can be drawn for the applicability of physical ideas to the phenomena of life, which would correspond to the distinction between the field of causal mechanical description and the proper quantum phenomena in atomic mechanics. However, the limitation which this fact would seem to impose upon the analogy considered will depend essentially upon how we choose to use such words as physics and mechanics. On one hand, the question of the limitation of physics within biology would, of course, lose any meaning, if, in accordance with the original meaning of the word physics, we should understand by it any description of natural phenomena. On the other hand, such a term as atomic mechanics would be misleading, if, as in common language, we should apply the word mechanics only to denote an unambiguous causal description of the phenomena. [中文](#)

I shall not here enter further into these purely logical points, but will only add that the essence of the analogy considered is the typical relation of complementarity existing between the subdivision required by a physical analysis and such characteristic biological phenomena as the self-preservation and the propagation of individuals. It is due to this situation, in fact, that the concept of purpose, which is foreign to

mechanical analysis, finds a certain field of application in problems where regard must be taken of the nature of life. In this respect, the rôle which teleological arguments play in biology reminds one of the endeavours, formulated in the correspondence argument, to take the quantum of action into account in a rational manner in atomic physics. [中文](#)

In our discussion of the applicability of mechanical concepts in describing living organisms, we have considered these just as other material objects. I need scarcely emphasise, however, that this attitude, which is characteristic of physiological research, involves no disregard whatsoever of the psychological aspects of life. The recognition of the limitation of mechanical ideas in atomic physics would much rather seem suited to conciliate the apparently contrasting points of view which mark physiology and psychology. Indeed, the necessity of considering the interaction between the measuring instruments and the object under investigation in atomic mechanics corresponds closely to the peculiar difficulties, met with in psychological analyses, which arise from the fact that the mental content is invariably altered when the attention is concentrated on any single feature of it. [中文](#)

It will carry us too far from our subject to enlarge upon this analogy which, when due regard is taken to the special character of biological problems, offers a new starting point for an elucidation of the so-called psycho-physical parallelism. However, in this connexion, I should like to emphasise that the considerations referred to here differ entirely from all attempts at viewing new possibilities for a direct spiritual influence on material phenomena in the limitation set for the causal mode of description in the analysis of atomic phenomena. For example, when it has been suggested that the will might have as its field of activity the regulation of certain atomic processes within the organism, for which on the atomic theory only probability calculations

may be set up, we are dealing with a view that is incompatible with the interpretation of the psycho-physical parallelism here indicated. Indeed, from our point of view, the feeling of the freedom of the will must be considered as a trait peculiar to conscious life, the material parallel of which must be sought in organic functions, which permit neither a causal mechanical description nor a physical investigation sufficiently thorough-going for a well-defined application of the statistical laws of atomic mechanics. Without entering into metaphysical speculations, I may perhaps add that any analysis of the very concept of an explanation would, naturally, begin and end with a renunciation as to explaining our own conscious activity. 中文

In conclusion, I wish to emphasise that in none of my remarks have I intended to express any kind of scepticism as to the future development of physical and biological sciences. Such scepticism would, indeed, be far from the mind of a physicist at a time when the very recognition of the limited character of our most fundamental concepts has resulted in such far-reaching developments of our science. Neither has the necessary renunciation as regards an explanation of life itself been a hindrance to the wonderful advances which have been made in recent times in all branches of biology and have, not least, proved so beneficial in the art of medicine. Even if we cannot make a sharp distinction on a physical basis between health and disease, there is, in particular, no room for scepticism as regards the solution of the important problems which occupy this Congress, as long as one does not leave the highroad of progress, that has been followed with so great success ever since the pioneer work of Finsen, and which has as its distinguishing mark the most intimate combination of the study of the medical effects of light treatment with the investigation of its physical aspects. 中文

(131, 457-459; 1933)

Therapy, Copenhagen, on August 15, 1932. The present article, conforming with the Danish version (*Naturens Verden*, 17, 49), differs from that published in the Congress report only by some formal alterations.

光与生命*

尼尔斯·玻尔

这篇文章出自尼尔斯·玻尔在哥本哈根举行的国际光疗大会上的讲话。大会本来想邀请玻尔向大家介绍一下光对于治疗疾病的好处，但实际上玻尔讲的是光在新量子理论中的概念对生命科学的潜在意义。玻尔说：虽然描述光量子行为的波动理论还不够完善，但仍可能把光看作是量子力学中的一个“粒子”。他指出：任何想精确测量光子轨迹的尝试都必然会破坏波的干涉现象。他说这一问题使人们不得不放弃对光现象的纯因果描述。

玻尔在第二部分中指出，量子理论的拓展远远超过了原子物理的范畴。植物的碳同化作用肯定包含着光与物质之间发生相互作用的量子本质，人眼只能看到几个光子说明它的结构反映了光学上的量子极限。玻尔将物理学和生物学中的不确定性进行了类比。对生物体过于精密的研究可能会对它们的重要器官产生干扰，就像物理学家为了研究粒子必须干扰它们一样。也许生命和意识是永远不能被解释清楚的，只能把它们当成不言自明的公理，物理中的量子现象也是如此。 [英文](#)

第一部分

作为一个研究领域仅限于非生命物质的物理学家，在接受盛情邀请来到这个科学界人士云集的大会介绍光对于治疗疾病的有利影响时，我还是有点犹豫的。因为我无法致力于这个对造福人类有重要贡献的精彩科学分支，我至多只能对纯粹的无机光学现象发表评述，光现象对古往今来的物理学工作者来说一直有着特殊的吸引力，一个重要的原因是光是我们的主要观测手段。然而，我认为，在这样的场合谈一谈物理学范畴内的研究成果对我们认识生物体在自然科学领域中的地位具有什么样

的意义也许是一件有趣的事情。

[英文](#)

尽管生物体中的秘密难以捉摸，但这个问题在科学发展的每一个阶段都会被提出来，因为科学上的探索就是要将对复杂现象的描述还原为简单的原理。然而现在，原子理论的最新进展表明，人们对自然现象的力学描述在本质上存在着不可抹杀的局限性，这一意想不到的发现重新燃起了大家对这个古老问题的兴趣。事实上，人们最先是在对光与物体之间相互作用的全面研究中认识到这一局限性的，该现象所揭示的特性无法与迄今为止已形成的物理学理论相统一。正如我将努力向大家说明的那样，物理学家们为解决这一问题所做出的努力，在某种程度上类似于生物学家对待生命现象时多多少少有点依据直觉的方式。但我马上要说明的是，光这种在物理学中可能是最不具有复杂性的现象，只是在这一点上与多样性远远超出科学分析范畴的生命现象相似。

[英文](#)

从物理学的观点看，光可以被定义为相隔一定距离的物体之间的能量传播。大家都知道，利用电磁学理论就可以简单地解释这样的能量传递，这也许可以被看作是对包括超距作用和接触力在内的经典力学的直接拓展。根据这一理论，光可以被描述为耦合的电磁振荡，它们与无线电广播中使用的普通电磁波一样，只不过具有较高的频率和较短的波长。事实上，我们之所以可以通过直接观察或适当的光学仪器来判断物体的位置是因为光具有直线传播的特性，而这种特性完全依赖于光的波长比相关物体和观测工具的尺度要小很多。

[英文](#)

然而，光具有波动性的思想不仅能为我们提供解释颜色现象的依据，在光谱学中颜色能提供有关物质内部结构的重要信息，而且它对于每一种光学现象的详细分析也是必不可少的。至于代表性的例子，我只需提及干涉条纹就可以了，当从一个光源发出的光沿着两条不同的路径投射到一个屏幕上时，就会出现干涉条纹。在这种情况下，我们发现在屏幕上两列波位相一致时，也就是说两束光的电磁振动方向相同时，分开的两个光束将在这些点上产生增强，而在电磁振荡方向相反也就是说两列波彼此异相时，光强将减弱甚至有可能消失。这些干涉条纹使人们能够精确地检测光传播的波动性，因而波动概念不再是一种通常意义上的假设，而有可能被认为是描述所观察到的现象中不可或缺的要素。

[英文](#)

尽管如此，大家都知道，近几年人们又开始讨论光的本质这个问题了，这是因为人们发现在能量传输中有一个特殊的原子性质，这个特殊性质无法用电磁理论来解释。事实上，所有的光效应都可以被看作是一个单独的过程，在每一个这样的过程中，发生了所谓的一个光量子交换，光量子的能量等于电磁振荡频率与基本作用量子（或称普朗克常数）的乘积。这个光的原子性与电磁理论所要求的能量传输连续性之间的明显对立使我们陷入了一个有关迄今为止在物理学中仍不清楚的性质的困境。因为尽管波动理论还明显不够完善，但是毫无疑问，我们仍可以用在经典力学思想框架下的任何其他的光传播理论来取代它。 英文

应该特别强调的是，引入光量子这个概念决不意味着对旧思想的回归，即认为光能的载体是有明确路径的实物粒子。实际上，任何尝试追踪单个光量子路径的行为都会干扰被研究的对象，这是所有光学现象共有的特征，波动性在描述光学现象时是不可缺少的；正如如果在光源和屏幕之间有两条路径，我们为了确保光只沿着其中的一条路径传播，就应该在另一条路径上引入不透光的物质，这样干涉条纹就会完全消失。因此，一方面是光传播的空间连续性，另一方面是光效应的原子性，它们应该被看作是一件事情相互补充的两个方面，从这个意义上说，每一个方面都代表了光现象的一个重要特征，尽管从力学角度上看它们是不可调和的，但也绝对不是完全对立的，因为要用力学方法进一步分析其中一个特征或另一个特征就需要排斥对方的实验装置。 英文

然而，这种情况使我们不得不放弃对光现象的完整因果描述而安于概率计算，原因是用电磁理论描述光的能量传输在统计学意义上仍然有效。这种计算是所谓一致论的典型应用，它显示出我们在努力通过对力学和电磁学概念的有限运用获得对原子现象的统计学描述，这似乎是经典物理理论的一个理性概括，虽然经典物理学认为必须把作用量子看成是非理性的。 英文

这种情形也许初看起来非常令人遗憾；但正如科学史上经常发生的，当我们从新发现中察觉到一个普遍适用性从未被人置疑过的思想存在本质上的局限时，我们就已经从相关现象中得到了更广的视野和更强的能力，而这种现象或许在以前就曾作为对立的情况出现过。因此，作

用量子象征着经典力学出现了前所未有的局限性，这种局限性给我们提供了理解原子具有特殊稳定性的线索，而原子所具有特殊稳定性是用经典力学理论描述所有自然现象的基本假设。经典力学理论无法理解原子是不可分割的，而毫无疑问通常突显了原子理论的特性；这一点至今没有本质上的更改，尽管后来的物理学已经用基本带电粒子替代了不可分割的原子，而且现在认为各种元素的原子以及化合物中的分子都是由电子和原子核这些基本粒子构成的。 [英文](#)

然而，我在这里并不想谈及这些基本粒子的固有稳定性问题，而是要探究构成这些结构所必需的稳定性。事实上，以能量存在持续传递可能性为特征的经典力学和电磁理论是不能与对元素和化合物性质的解释达成一致的。的确，我们甚至不能用经典理论来解释刚体的存在，而为了测量空间和时间中的有序现象必须有赖于刚体。但是，由于作用量子的发现，我们了解到原子或分子能量的每一次改变都必须被看作是一个单独的过程，在这样的过程中原子从它的一个定态跃迁到了另一个定态。此外，因为在一个原子发射光或吸收光的跃迁过程中只会有一个光量子产生或消失，所以我们能够通过光谱观测直接测量每一个定态的能量。人们通过对原子碰撞和化学反应中能量交换的研究已经非常有效地确证了由上述方法得到的数据。 [英文](#)

近些年来，原子理论取得了长足的进步，它足以为我们提供计算定态能值和跃迁概率的方法，因而我们根据一致论得到的有关原子性质的结论在完整性和自洽性方面几乎与用牛顿力学解释天文观测结果的水平不相上下。虽然只有在引入新的符号处理技巧之后才有可能合理地解决原子力学的困境，但在分析光学现象时的经验对于我们评估原子力学的发展仍然有非常重要的意义。因此，确立定态概念是对用力学法分析原子内部运动的补充；同样，引入光量子概念是对电磁辐射理论的补充。任何追踪跃迁详细过程的尝试都会使原子和测量仪器之间发生不可控的能量交换，会彻底干扰我们要研究的能量转移过程。 [英文](#)

经典意义中的因果描述只有在相互作用远大于作用量子时才可能成立，因此，在基本不干扰它们的情况下是有可能对这些现象进行细分的。而在不满足上述条件的情况下，我们就不能忽略测量仪器与被研究物体之间的相互作用，为了得到完整的力学描述，我们需要考虑使用不

同的测量方法，而这些测量只有通过相互排斥的实验装置才能得到。为了充分了解用力学分析原子现象的基本局限性，我们必须清楚地、深刻地认识到，在物理测量中，绝不可能直接将物体和测量仪器的相互作用考虑在内。因为当仪器被用作观察手段的时候，就不能把它们包括在研究对象之中。正如广义相对论所表述的观点，物理学现象在本质上依赖于用于描述它们在空间和时间中坐标的参考系，因而原子物理学中的互补概念就用来表示基本的局限性，即我们根深蒂固的理念是现象不依赖于观测手段而独立存在。

英文

（姜薇 翻译；张泽渤 审稿）

第二部分

人们对力学基本理论的修正引申出这样一个问题，即一个物理学解释可能会意味着什么，然而这不仅仅是解释原子理论中的现象所必需的，也为讨论物理学与生物学之间的相关性奠定了一个新的基础。当然，这绝不意味着我们在原子现象中发现的特征与普通的物理学效应相比更接近于生物体的性质。初看起来，原子力学所具有的基本统计学特点似乎难以与人们对所有生物体都具有的超精细组织的解释相匹配，这种超精细组织可以把本物种的所有特征植入一个微小的生殖细胞中。

英文

然而，我们绝不能忘记：原子过程所特有的规律性不能用因果机制表示，只能借助互补模式描述，这种规律性至少在对生物体行为的描述和对无机物特性的解释上具有同等的重要性。因此，在植物的碳同化、同时也是动物养分的主要来源的生成过程中，我们正在研究的是一个现象，为了理解这个现象，必须确确实实地去考虑参与光化学反应的个体特性。另外，像在植物同化与动物呼吸作用中扮演重要角色的叶绿素和血红蛋白，它们所具有的复杂程度如此高的化合物的特性，也明显地表现出原子结构独特的稳定性。

英文

然而，由化学知识类推解释生命体，诚然会比在古代将生命比作火更贴切，却不会强于人们常说的生命体与纯机械制造物如钟表发条之间的类比。毫无疑问，必须在特定的生物组织中探寻对生命本质特征的理

解，在研究这些组织的特征时，将用普通力学进行分析并且以与无机物不同的方式交织着一些典型的原子特性。 [英文](#)

通过研究眼睛的构造与功能，我们得到了有关这个已经发展得十分精细的组织的有效信息，也再一次地显示光现象的简单特性是非常有用的。我无需在这里详述细节，但想回顾一下眼科学是如何向我们揭示作为一种光学装置的人眼的理想特征的。实际上，由于光的波动性，干涉图像的尺寸规定了眼成像的限度，而干涉图像的尺寸与视网膜的分区相符，其中每个分区都有单独的神经与脑相连。此外，因为在这样的视网膜分区中，只要吸收几个光量子，或者也许只要吸收一个光量子就足以产生视感，有人甚至说眼睛的敏感程度已经达到了光效应的原子特性所设置的极限。在两个方面，眼睛的效能同那些连有合适放大器的高性能望远镜或显微镜一样，可以观测到单个过程。利用这样的仪器确实能从根本上提高我们的观察能力，但由于光的性质所设置的极限，在人们可以想象得出的仪器中，没有一种可以与眼睛的灵敏度相比。现在，眼睛这种只有借助物理学的最新发展才能被深刻认识的理想化结构也说明了其他的器官，不管它们的作用是接收来自周围环境的信息，还是对感觉印象做出反应，都同样会表现出与自身功能相适应的特点，在这类情况下，由作用量子所代表的个性特征以及一些放大机制起着关键性的作用。目前，我们尚无法知道除眼睛外其他器官的极限，而眼睛只取决于比其他物理现象简单得多的光现象。 [英文](#)

然而，仅仅认识到运用原子论基本原理来说明生物体功能的必要性还不足以全面解释生物学现象。因此，我们要讨论的问题是，在我们能够用物理学观点解释生命现象之前，是否还缺少一些分析自然现象所需的基本特征。如果不去考证我们通过物理学解释而理解的内容，就很难得到这个问题的答案，更何况现实中生物现象的类别多得无法列举，这要比发现作用量子对我们的推动意义更深远。一方面，通过生理学研究不断揭示出的神奇特征与无机物的特征有着显著的差别，这使许多生物学者怀疑用纯物理学的方法是否可以真正理解生命的本质。另一方面，人们通常称为活力论的观点，不能正确地解释有一种特殊的生命力掌控着所有有机体的古老假设，在物理学中也不存在这样的力。我认为我们都赞同牛顿的观点，即科学的真正基础在于确信自然界在相同条件下会

表现出同样的规律性。因此，如果我们能够把对生命体机理的分析推进到原子现象的层面，我们就不应该期待会发现任何有别于无机物的特点。 [英文](#)

然而，当我们面临进退两难的困境时，我们必须记住，生物学和物理学的研究条件并不完全对应，因为前者要受到研究对象必须是活体的限制，而在后者中则不存在这样的限制。因此，如果我们试图对动物的器官展开研究以便描述单个原子在生命活动中的功能时，我们无疑会杀死一只动物。在对活体进行的每一次实验中，都肯定会存在因个体生理条件不同而导致的不确定性，这个观点本身说明，在这方面，即使我们允许生物体具有最低的自由度，也足以让生命体可以对我们隐藏其最根本的秘密。根据这个观点，我们应该把生命的存在看作是不能被解释的基本事实，而以此作为生物学研究的起点，这与作用量子类似，在经典机械物理学中，作用量子被看作是一种非理性的成分，而它与基本粒子一起构成了原子物理学的基础。从这个意义上说，宣称用物理或化学方法不可能解释生命体的功能就类似于用经典力学不能理解原子的稳定性。 [英文](#)

然而，在进一步研究这个类比时，我们一定不要忘记物理学中的问题和生物学中的问题存在着本质上的不同。在原子物理学中，我们是从形式最简单的物质的性质入手的，而在生物学研究中具有根本性意义的是物质系统的复杂性，因为即便是最原始的生物也包含大量的原子。的确，经典力学的应用范围广泛，其中包括我们在研究原子物理时使用的测量仪器，要想在描述由大量原子组成的物体中应用经典力学就必须在很大程度上忽略伴随着作用量子的互补性。然而，在生物学研究中，人们通常不能像在原子物理学基础实验中那样控制单个原子所处的外部条件。实际上，我们甚至不知道哪些原子是真正属于生物体的，因为任何生命活动都伴随着物质的交换，原子不断地被构成这个生物体的组织吸入和排出。 [英文](#)

物理学研究和生物学研究之间的这种本质不同暗示着人们无法明确地划分出在运用物理学原理解释生命现象时的界限，这也相当于因果力学描述的场和原子力学中固有量子现象之间的区别。然而，上述事实对这个类比的限制似乎从根本上取决于我们如何运用像物理学和力学这样

的词。一方面，如果依照物理学这个词的原始意义，我们就应当把它理解为是对所有自然现象的描述，那么认为物理学在生物学中的运用受到限制就失去了意义。另一方面，如果在通用语言中我们用力学这个词只表示对现象的清晰的因果关系的描述，那么像原子力学这样的术语就会引起人们的误解。 [英文](#)

我不打算在这里进一步讨论这些纯逻辑学上的观点，但只想补充一点，即典型的互补性关系构成了这个类比的本质，这种关系存在于物理分析所需的细分与诸如自卫本能和个体繁殖这样的典型生命现象之间。事实上，正是由于这个原因，在力学分析中不曾有过的目的性概念，在必须考虑生命本质的领域中得到了应用。从这个方面来说，目的论在生物学中所扮演的角色使人回想起人们曾努力用对应的自变量将作用量子以一种理性模式引进到原子物理中。 [英文](#)

在我们讨论用力学概念描述生物体时，我们对待它们和对待其他实物没有什么两样。然而，我无需强调这种生理学研究中的特有态度并没有任何对生命的心理问题的漠视。人们对力学概念在原子物理中所受限制的认识似乎更适合于理解生理学与心理学在观点上的明显对立。的确，在原子物理学中需要考虑测量仪器与研究对象之间的相互作用十分类似于在心理学分析中遇到的特定困难，该困难起源于当注意力集中在任何一个单一的功能上时，心理内容总在不断变化。 [英文](#)

当适当考虑生物学的特性时，这个类比为阐明所谓的身心并行说提供了一个新的起点，这样说将使我们过于偏离我们要讨论的题目。然而，关于这一点，我想强调的是，这里谈到的观点完全不同于想借助在分析原子现象时因果描述受到的局限而极力推崇物质现象很可能会直接受到精神影响的看法。例如，当人们认为也许可以利用特定原子过程的规律来研究在有机体中的意志及其作用域时，原子理论只能为其建立概率的计算，我们正在谈论的这个观点与刚才提到的身心并行说水火不相容。确实，依据我们的观点，意志对自由的感受必须被看成是意识生活所特有的性质，人们必须在器官的功能中寻找与其对应的物质，既不允许力学因果描述也不能允许充分彻底地运用原子力学中的统计规律来进行物理学研究。除了形而上学的思索以外，我也许可以补充说，所有对一个解释的概念的分析都以放弃对我们自身意识行为的解释开始，也以

放弃对意识行为的解释而结束。

英文

最后，我想强调的是，我并不希望大家把我的话理解为是对未来物理学和生物学发展的怀疑。实际上，现在这个时代的物理学家绝不会抱有怀疑论的思想，因为科学已经在人们认识到最基本的概念存在局限性的基础上发生了深刻的变革。近期人们在生物学所有分支取得的惊人进展并没有受到放弃对生命问题本身的解释的影响，而且这些进展也相当有益于医术的发展。即使我们不能从物理学角度明确地区分健康与疾病，我们也没有理由怀疑在本次会议上所达成的对重要问题的解释，由于我们没有偏离科学发展的道路，因此从芬森的早期工作到现在已经取得了很大的进展，而此项工作明显的标志是光疗医学效应的研究和物理学研究的最紧密的结合。

英文

（吴彦 翻译；张泽渤 审稿）

* 这是1932年8月15日玻尔在于哥本哈根召开的国际光疗大会开幕式上发表的讲话。本文与丹麦版（《自然世界》，第17卷，第49页）是一致的，但与公开出版的会议报告不完全一样，区别在于把一些口语化的文字改成了比较正式的形式。

Nuclear Energy Levels

G. Gamow

Although physicists still lacked any clear understanding of nuclear structure—the possibility that electrons inhabited the nucleus was still widely considered, for example—quantum theory was proving useful for interpreting nuclear spectroscopy. As George Gamow here points out, one could gainfully consider nuclear constituents to be bound by unknown forces inside a square-profiled well with infinitely high sides: a model tractable to quantum theory, which could predict the energies of states of different angular momentum. Gamow shows that spectroscopic data from an isotope called radium C' revealed transitions close to 11 of the 21 predicted by the theory. Further studies might indicate how the square-well model should be altered to make the theory more accurate. [中文](#)

IT is a plausible hypothesis that the forces acting on a particle inside the nucleus are comparatively weak in the internal region and increase rapidly to the boundary of the nucleus, the potential distribution being represented by a hole with more or less flat bottom and rather steep walls¹. If we approximate this model by a rectangular hole with infinitely high walls, the energy levels of a moving particle will be determined by the roots of Bessel functions and can be easily calculated. For the real model, however, this theoretical level system will be deformed owing to the fact that the walls are neither quite

steep nor infinitely high, producing compression of the upper part of the level system. 中文

The best nucleus for testing this hypothesis is that of radium C', for which a lot of experimental evidence is available. For this nucleus we have the measurements by Rutherford² of long range α -particles (nine groups) giving us approximate positions of nuclear levels. The investigations of Ellis³ give for a number of γ -lines (nine lines) their absolute intensities and, what is most important, the values of internal conversion coefficients enabling us, as has been shown by Taylor and Mott⁴, to tell the dipole transitions from quadrupole transitions.

中文

These data are sufficient to construct the level system of the radium C' nucleus, the main part of which is represented in Fig. 1, together with the theoretical one. 中文

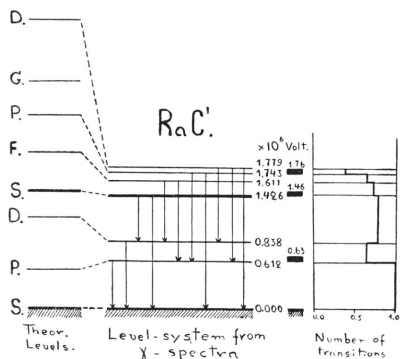


Fig. 1 中文

We see immediately that not every level corresponds to a long range α -group; this is, however, to be expected, as the probability of α -disintegration from a level with large j is comparatively small, due to the additional barrier of centrifugal forces (for equal energies the probability for an α -particle escaping from P-, D-, F-, G-levels will be respectively 1.3, 4, 16 and 105 times less than for the S-level). The observed transitions are given in the accompanying table. 中文

Constructed		Observed		Constructed		Observed	
$h\nu \times 10^{-6}$ volt	Δj	$h\nu \times 10^{-6}$ volt	Δj	$h\nu \times 10^{-6}$ volt	Δj	$h\nu \times 10^{-6}$ volt	Δj
0.588	2	0.589	..	1.131	0	1.130	0 ; 2
0.612	1	0.612	1	1.167	1	1.168	..
0.773	1	0.773	1	1.426	0→0	1.426	0→0
0.838	2	0.839	..	1.743	1	1.744	..
0.941	0	0.941	0 ; 2	1.779	2	1.778	0 ; 2
0.999	2	1.000	..				

中文

From twenty-one mathematically possible transitions, eleven are actually found and, as can be seen from the table, have appropriate energies and obey the exclusion principle. From the remaining ten lines, two are not to be expected corresponding to $F \rightarrow S$ -transitions, four fall in a spectral region not yet investigated and four are not observed, possibly due to comparatively small intensity. It is also of interest to construct an excitation diagram, building up the sums of the intensities for all lines crossing a given level interval. From this diagram we see that there must be a γ -line 0.226×10^6 volt with absolute intensity about 0.2 which at present is not known. 中文

The similarity of theoretical and real level systems proves the correctness of our picture of the potential inside the nucleus, and the deviations between these systems must permit us to calculate the real potential distribution. 中文

(131, 433; 1933)

G. Gamow: Research Institute of Physics, University, Leningrad, Jan. 30.

References:

1. Gamow, *Proc. Roy. Soc., A*, **126**, 632 (1930).
2. Rutherford, *Proc. Roy. Soc., A*, **131**, 684 (1931).
3. Ellis, *Proc. Roy. Soc., A*, **129**, 180 (1930).
4. Taylor and Mott, *Proc. Roy. Soc., A*, **138**, 665 (1932).

核能级

乔治·伽莫夫

虽然物理学家们对核结构还缺乏明确的认识，比如很多人仍然认为电子可能存在于原子核当中，但实践证明量子理论是可以用于解释核谱的。正如乔治·伽莫夫在文中所述：可以假设原子核中的各个成分被未知的力束缚在一口无限深的方井中，这样的假设是有益的：量子理论可以通过对这个模型的计算得到不同角动量状态的能量。伽莫夫指出：在该理论预测的21个跃迁中有11个接近于从镭C'同位素光谱中得到的数据。接下来的研究方向可能是：对方井模型进行怎样的调整才能使该理论更为精确。 [英文](#)

我们似乎可以合理地假设作用于核内粒子上的力在核的内部区域相当弱，随着接近核的边界而迅速增大，势能的分布可以用一个近似平底深壁的孔来表示^[1]。如果我们在模型中使用的是一个壁高为无限大的矩形孔，就可以由贝塞尔函数的根得到运动粒子的能级，计算方法非常简单。然而对于实际上的模型，由于壁并不是很陡，也不是无限高，因此理论能级系统会发生变化，能级系统的上部会被压缩。 [英文](#)

镭C'的核最适于验证这个假说，因为我们有很多关于这种核的实验证据。卢瑟福通过对长程 α 粒子（9组）的测量为我们提供了镭C'核能级的近似位置^[2]。埃利斯^[3]的研究给出了许多 γ 谱线（9条谱线）的绝对强度以及内转换系数的值，后者为我们提供了非常重要的信息，正如泰勒和莫特曾经说过的那样^[4]，内转换系数值是我们分辨四极跃迁和偶极跃迁的依据。 [英文](#)

我们用这些数据足以构建镭C'核的能级系统，能级的主体部分示于图1，图中还标出了理论值。 [英文](#)

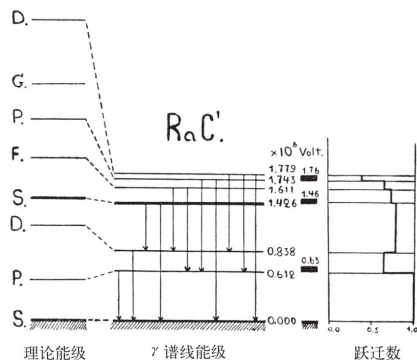


图1 英文

我们很快发现并不是每一个能级都对应于某个长程 α 粒子组；然而，这有可能是由于大 j 能级的 α 衰变概率很小的缘故，因为离心力会产生附加势垒（如果能量相同，一个 α 粒子从 S 能级逃逸的概率分别是从 P 、 D 、 F 、 G 能级逃逸的概率的1.3、4、16和105倍）。观测到的跃迁列于下表中。

英文

理论值		观测值		理论值		观测值	
$hw \times 10^{-6} \text{ V}$	Δj	$hw \times 10^{-6} \text{ V}$	Δj	$hw \times 10^{-6} \text{ V}$	Δj	$hw \times 10^{-6} \text{ V}$	Δj
0.588	2	0.589	..	1.131	0	1.130	0 ; 2
0.612	1	0.612	1	1.167	1	1.168	..
0.773	1	0.773	1	1.426	0 $\rightarrow$ 0	1.426	0 $\rightarrow$ 0
0.838	2	0.839	..	1.743	1	1.744	..
0.941	0	0.941	0 ; 2	1.779	2	1.778	0 ; 2
0.999	2	1.000	..				

英文

从数学的角度上看共有21种可能的跃迁，实际上只发现了其中的11种，如上表所示，能量值与理论预测相符并遵从不相容原理。至于剩下的10条谱线，其中2条 $F \rightarrow S$ 跃迁并不是预期应当有的谱线，另外4条处于研究范围之外的谱区，还有4条可能因强度太小而未被观测到。另一件有意思的事情是，我们可以通过构建跃迁图来计算穿过某个给定能级间隔的所有谱线强度之和。从这张图中我们发现了一条现在还未知的 γ 线，这条 $0.226 \times 10^6 \text{ V}$ 的 γ 线的绝对强度大约为0.2。

英文

理论与实际能级系统的相似性证实了我们对核内部势能的预测，而根据理论和实测能级系统之间的偏差，我们一定能计算出实际的势能分布。

英文

(沈乃澍 翻译；尚仁成 审稿)

New Evidence for the Positive Electron

J. Chadwick *et al.*

Here James Chadwick, along with Patrick Blackett and Giuseppe Occhialini, confirms the existence of a positively charged anti-particle of the electron, initially reported by Carl Anderson from cloud-chamber experiments. Chadwick and colleagues placed pieces of polonium and beryllium just outside a cloud chamber, and near a lead target placed just inside the chamber. Alpha particles from the polonium excited neutrons or gamma rays from beryllium that in turn stimulated the emission of particles from lead. These left tracks in the cloud chamber with the properties expected for a positively charged electron. Further experiments strongly suggested that the unknown particles had the same mass as electrons, but a positive charge. They were later called positrons, the first known example of antimatter. [中文](#)

THE experiments of Anderson¹ and of Blackett and Occhialini² on the effects produced in an expansion chamber by the penetrating radiation strongly suggest the existence of positive electrons—particles of about the same mass as an electron but carrying a positive charge.

[中文](#)

Some observations of the effects produced by the passage of neutrons through matter, and the experiments of Curie and Joliot³ in which

they observed retrograde electron tracks in an expansion chamber, led us to consider the possibility that positive electrons might be produced in the interaction of neutrons and matter, and we have recently obtained evidence which can be interpreted in this way. [中文](#)

A capsule containing a polonium source and a piece of beryllium was placed close to the wall of an expansion chamber. On the inside of the wall was fixed a target of lead about 2.5 cm. square and 2 mm. thick. This lead target was thus exposed to the action of the radiation, consisting of γ -rays and neutrons, emitted from the beryllium. Expansion photographs were taken by means of a stereoscopic pair of cameras. A magnetic field was applied during the expansion, its magnitude being usually about 800 gauss. [中文](#)

Most of the tracks recorded in the photographs were, from the sense of their curvature, clearly due to negative electrons, but many examples were found of tracks which had one end in or near the lead target and showed a curvature in the opposite sense. Either these were due to particles carrying a positive charge or they were due to negative electrons ejected in remote parts of the chamber and bent by the magnetic field so as to end on the lead target. Statistical examination of the results supports the view that the tracks began in the target and therefore carried a positive charge. [中文](#)

Strong evidence for this hypothesis was acquired by placing a metal plate across the expansion chamber so as to intercept the paths of the particles. Only a few good photographs have so far been obtained in which a positively curved track passes through the plate and remains in focus throughout its path, but these leave no doubt that the particles had their origin in or near the lead target and were therefore positively charged. In one case the track had a curvature on the target side of the plate, a sheet of copper 0.25 mm. thick, corresponding to a value of $H\rho$ of 12,700; on the other side the curvature gave a value $H\rho = 10,000$. This indicates that the particle travelled from the target

through the copper plate, losing a certain amount of energy in the plate. The change in the value of H^ρ in passing through the copper is roughly the same as for a negative electron under similar conditions. The ionising power of the particle is also about the same as that for the negative electron. These observations are consistent with the assumption that the mass and magnitude of the charge of the positive particle are the same as for the negative electron. [中文](#)

The manner in which these positive electrons are produced is not yet clear, nor whether they arise from the action of the neutron emitted by the beryllium or from the action of the accompanying γ -radiation. It is hoped that further experiments now in progress will decide these questions. [中文](#)

Our thanks are due to Mr. Gilbert for his help in the experiments. [中文](#)

(131, 473; 1933)

J. Chadwick, P. M. S. Blackett, G. Occhialini: Cavendish Laboratory, Cambridge, March 27.

References:

1. Anderson, *Science*, **76**, 238 (1932).
2. Blackett and Occhialini, *Proc. Roy. Soc., A*, **139**, 699 (1933).
3. Curie and Joliot, *L'Existence du Neutron* (Hermann et Cie, Paris).

有关正电子的新证据

詹姆斯·查德威克等

在这篇文章中，詹姆斯·查德威克、帕特里克·布莱克特和朱塞佩·奥基亚利尼证实了一种带正电的粒子的存在，它是电子的反粒子，这种粒子是卡尔·安德森在云室实验中首先发现的。查德威克和同事把一小块钋和铍放在云室外靠近云室内铅靶的地方。钋发射的 α 粒子从铍中激发出中子或 γ 射线，随后又使铅发射出粒子。这些粒子在云室中留下的径迹显示出了一个带正电的电子所具有的性质。更多的实验表明这种未知粒子的质量和电子相同，但带正电。后来它们被命名为正电子，是人们发现的第一种反物质。 [英文](#)

安德森^[1]以及布莱克特与奥基亚利尼^[2]利用贯穿辐射在膨胀云室中产生的效应有力地证明了正电子的存在——一种与电子质量大致相等但带有正电荷的粒子。 [英文](#)

人们在中子穿过物质时观察到的一些现象以及居里和约里奥^[3]在膨胀云室中观察到反向电子径迹的实验使我们想到，正电子可能是在中子与物质发生相互作用时产生的，而且我们最近得到了可以用这种想法来解释的实验证据。 [英文](#)

将装有钋放射源和铍金属片的密封容器放在靠近膨胀云室外壁的地方。在云室的内壁上固定一个面积为2.5 cm见方，厚2 mm的铅靶。这个铅靶会受到从铍中辐射出的一种由中子和 γ 射线组成的射线的照射。膨胀时的照片是利用立体像对照相机拍摄的。在膨胀过程中给云室外加一个磁场，强度通常为800高斯。 [英文](#)

从弯曲方向来看，照片上记录的大多数径迹明显是由负电子产生的，但在实验中多次发现，有一些径迹的一端位于铅靶或铅靶附近并且

向相反方向弯曲。之所以会出现这种现象，或许是因为产生这些径迹的粒子带正电荷，又或许是因为产生于云室远端的负电子在磁场作用下发生偏转，从而使它们的径迹最终在铅靶处结束。对该结果的统计分析支持了径迹始于铅靶的观点，所以产生该径迹的粒子是带正电的。 [英文](#)

我们通过在膨胀云室中横放一块金属板以阻挡粒子路径的方法得到了支持这个假说的有力证据。虽然到目前为止，我们仅得到了几张效果较好的照片，照片上有一条明显弯曲的径迹穿过金属板，并且整条路径都比较清晰，但上述实验结果清清楚楚地说明这些粒子产生于铅靶或铅靶附近，因而带正电。在使用0.25 mm厚的铜板进行的一次实验中，我们在有铅靶的那一侧发现径迹出现弯曲，相应的 H^{ρ} 值为12,700；而在铜板的另一侧，相应的值为 $H^{\rho} = 10,000$ 。这表明粒子从靶出发穿过铜板时，在铜板内损失了一部分能量。在穿过铜板前后粒子 H^{ρ} 值的变化与类似情况下负电子产生的结果大致相等。这种粒子的致电离能力也与负电子大致相同。以上实验结果都说明认为这种带正电的粒子与负电子质量相同且电荷数相同的假说是成立的。 [英文](#)

我们现在还不清楚这些正电子是怎么产生的，也不知道它们是在铍发射的中子还是在随之发射的 γ 辐射的作用下产生的。希望正在进行的后续实验能够解决这一问题。 [英文](#)

感谢吉尔伯特先生在实验中给予我们的帮助。 [英文](#)

(王锋 翻译；李军刚 审稿)

Nature of Cosmic Rays*

A. H. Compton

This address by Arthur Compton to a meeting of the American Physical Society describes recent studies of the geographical distribution of cosmic rays, and their variation with altitude. A marked increase in cosmic-ray intensity in temperate and polar latitudes, compared with tropical zones, could be explained if the primary cosmic rays were electrons arriving in two energy ranges, the higher-energy particles being largely unaffected by the Earth's magnetic field while those in the lower-band are strongly deflected and therefore unable to reach the tropics. The data argue against the particles being photons, but cannot distinguish between ordinary electrons, "positively charged electrons", or protons or alpha particles. Today we know that most primary cosmic rays are protons. [中文](#)

THERE are three kinds of experiments which seem to afford direct evidence regarding the nature of cosmic rays. These are: (1) the Bothe-Kolhörster double counter experiment, which compares the absorption of the particles traversing the counters with the absorption of cosmic rays; (2) measurements of the relative intensity of cosmic rays over different parts of the earth, designed to show any effect due to the earth's magnetic field; and (3) studies of the variation of cosmic ray intensity with altitude, which should follow different laws according as the rays are electrons or photons. [中文](#)

(1) The Bothe-Kolhörster experiment serves to measure the absorption in a block of gold or lead of the high-speed electrified particles that produce coincident impulses in two neighbouring counting chambers. It is found that this absorption is surprisingly small, about the same, in fact, as that of the cosmic rays themselves. [中文](#)

The simplest interpretation of this similarity in absorption is to suppose that the high-speed particles in question are the cosmic rays. There is, however, the alternative possibility that the primary cosmic rays are photons which eject high-speed electrons as recoil electrons when the photons are stopped, and that these recoil electrons are absorbed at about the same rate as the primary rays themselves. Theoretical calculations indicate that the recoil electrons should be absorbed five or ten times as rapidly as the photons which give rise to them. These calculations are somewhat uncertain because of extrapolation far beyond the wave-length region where the existing formulae have been tested. For this reason, the equal absorption coefficients of the cosmic rays and the high-speed particles does not necessarily rule out the possibility that the particles in question may be recoil electrons excited by the cosmic rays. It would, nevertheless, be surprising if the formulae were in error by so large a factor as five or ten, as would be implied if the coincidences are due to secondary electrons. [中文](#)

(2) If the cosmic rays consist of electrified particles coming into the earth's atmosphere from remote space, the earth's magnetic field should affect their geographical distribution. This effect has been investigated theoretically by Størmer, Epstein, and recently much more completely by Lemaître and Vallarta. It appears that for energies less than 10^9 electron volts, electrons approaching the earth can reach it only at latitudes north of about 60° . For energies greater than about 5×10^{10} volts the geographical distribution is not affected by the earth's magnetic field. For intermediate energies, there will be a

difference in intensity with latitude according to the distribution of energy of the incoming electrons. 中文

Experimental studies of the relative intensity of cosmic rays in different parts of the world have been made by J. Clay, who made several trips between Java and Holland, and found consistently a lower intensity near the equator; Millikan and Cameron, who found but slightly lower intensity in the lakes of Bolivia than in the mountain lakes of California, and no difference between Pasadena and Churchill close to the north magnetic pole; Bothe and Kolhörster, who carried a counting tube from Hamburg (53° N.) to Spitsbergen (81° N.) and back, and detected no variations in the cosmic rays larger than their rather large experimental error; Kennedy, who, under Grant's direction, carried similar apparatus from Adelaide, Australia, to Antarctica, and likewise found no measurable change; and Corlin, who on going from 50° N. to 70° N. in Scandinavia found some evidence of a maximum at about 55° N. The prevailing opinion regarding the significance of these measurements has thus been expressed by Hoffman in a recent summary: "The results so far have on the whole been negative. Most of the observers conclude that within the errors of experiment the intensity is constant and equal, and those authors who do find differences give their results with certain reservations." 中文

During the past eighteen months, Prof. Bennett of the Massachusetts Institute of Technology, Prof. Stearns of the University of Denver, and I have organised a group of ten expeditions, with some sixty physicists, and we have attempted to make as extensive a study of the geographical distribution of cosmic rays as could be done in a limited period of time. Fig. 1 shows the position of the eighty-one stations in different parts of the world at which measurements have been made. These stations are about equally divided between the northern and southern hemispheres. They have extended from latitude 46° S. to

latitude 78° N., and from sea level to about 20,000 ft. (Figs. 2 and 3). When these data are brought together, they show a marked difference in intensity between the cosmic rays at temperate and polar latitudes, as compared with the tropical latitudes. At sea level the difference in intensity is about 14 percent, at 2,000 metres about 22 percent, and at 4,400 metres about 33 percent. The change between the intensity for tropical as compared with that for temperate latitudes occurs rather sharply between geomagnetic latitudes 25° and 40° . 中文

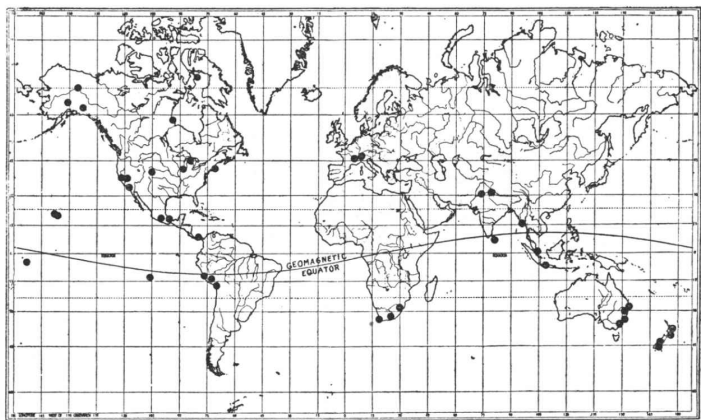


Fig. 1. Map showing major stations at which associated expeditions have made cosmic ray measurements during 1932. 中文

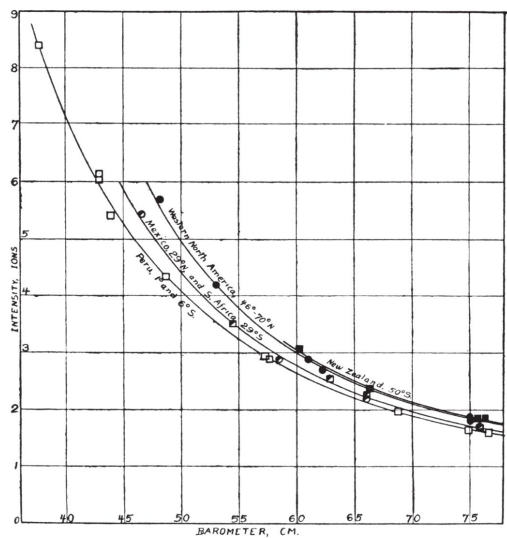


Fig. 2. Typical intensity-barometer curves, showing variation of intensity with altitude in different parts of the world. Circles, northern hemisphere; squares, southern hemisphere.

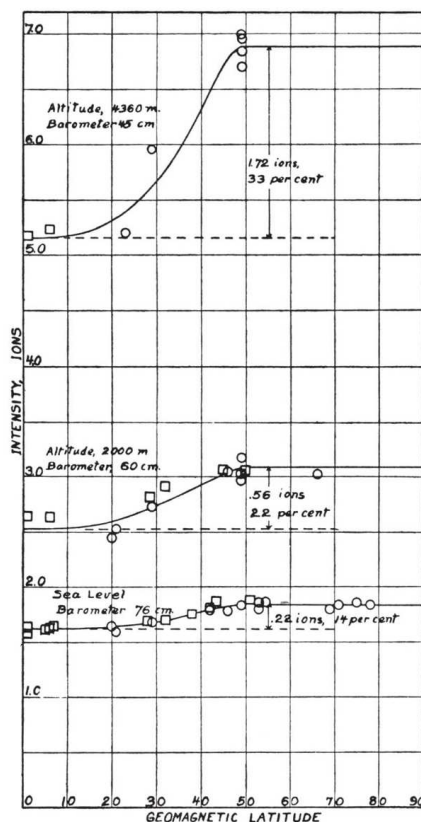


Fig. 3. Variation of cosmic ray intensity with geomagnetic latitude, as found for three different altitudes. The variation is more prominent at high altitudes. Curves calculated from Lemaître-Vallarta theory. 中文

Comparison of the experimental data with the theory of Lemaître and Vallarta shows that the distribution of cosmic rays is about that to be expected if the rays consist of electrons entering the earth's atmosphere in two energy groups. One of these is of such great energy that it is not appreciably affected by the action of the earth's field. This group comprises in the temperate zone 88 percent of the total radiation at sea level, and might, so far as these experiments are concerned, be classified as photons. At 4,400 metres this component constitutes 75 percent of the total radiation. The second component is less penetrating and represents particles with an energy, if they are electrons, of about 7×10^9 electron volts. It is these particles which

reach the earth at temperate latitudes but fail to reach it near the equator. [中文](#)

It may be remarked that even these less-penetrating cosmic rays have energies which are much larger than those that could be accounted for as recoil electrons resulting from photons, if these photons were to constitute the main body of the cosmic rays. According to Millikan, measurements of the absorption of the cosmic rays at sea level indicate that their energy, if they are photons, is of the order of 2×10^8 electron volts. This is so much less (a factor of 35) than that of the electrons responsible for the difference in intensity between temperate and tropical zones, that we would seem to be safe in concluding that the particles reaching the earth are not of the recoil type. On the other hand, the energy of 7×10^9 electron volts demanded by the Lemaître-Vallarta theory for these particles would mean a range taken along the particle's trajectory of about three times the thickness of the earth's atmosphere. This is in accord with the fact that these rays penetrate the earth's atmosphere, but with difficulty. [中文](#)

This geographical study of the cosmic rays thus indicates that the less penetrating part of the cosmic rays, at least, consists of high-speed electrified particles. Regarding the more penetrating component, we conclude that if they are electrified particles, they must have an energy of 3×10^{10} electron volts or more. [中文](#)

(3) During the past two years, extensive experiments have been carried out studying the variation in the intensity of cosmic rays with altitude. The highest altitudes have been those reached by Regener with his sounding balloon and Piccard with his famous stratosphere balloon. We have also paid especial attention to this problem in our mountain experiments. In Fig. 4 the data from mountain and balloon observations are compared. These data show a rapid increase in intensity with altitude, continuing nearly exponentially to an altitude of 15 km., and from there approaching a limiting value as the

apparatus is carried close to the top of the atmosphere.

中文

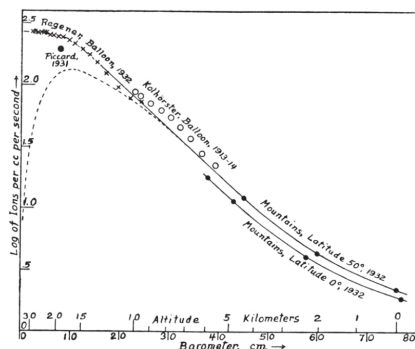


Fig. 4. Combined balloon and mountain data on intensity as function of altitude. Broken line, anticipated values for photons.

中文

If we suppose that the cosmic rays enter the earth's atmosphere as photons, any secondary electrons that may have been associated with them in space will have been removed by the action of the earth's magnetic field. We should thus have a beam of pure photons entering the atmosphere. At the surface of the atmosphere these photons will produce very little ionisation, for the ionisation results directly from the secondary electrons that pass through the chamber. The secondary electrons, however, arise only at the absorption of the primary photons, and will not approach their normal intensity until the photons have traversed a thickness of air about equal to the range of the electrons. This means that at very high altitudes the ionisation due to a beam of photons entering the earth must be almost zero. The ionisation current should rather approach a maximum at a depth in the atmosphere at which the cosmic rays are somewhat less than half absorbed, and should then gradually diminish in intensity as sea level is approached. Our high mountain experiments confirm the recent balloon experiments as indicating that no such high altitude maximum exists. This would seem to rule out the possibility that the cosmic rays can be photons entering the earth's atmosphere from remote distances.

中文

If we suppose, on the other hand, that the cosmic rays are electrons

entering the atmosphere from above, we should expect very much the kind of intensity-altitude curve that the present experiments show. It is well known that the ionisation per unit path by high speed electrons remains almost constant over a wide range of energies. Thus, if a beam of such electrons enters the atmosphere, it will produce nearly uniform ionisation down to such depths that an appreciable number of the electrons are stopped by the air. If the initial electrons were all travelling downward, there would be a rather definite limit or range where there would be a rapid reduction in the ionisation by the cosmic rays. If, however, the initial electrons entered in all directions, some of them would be stopped even in the upper layers of the atmosphere. Thus, supposing that the cosmic rays consist of electrons entering the earth's atmosphere from outer space, the general characteristics of the intensity-altitude curve can be readily accounted for.

[中文](#)

If Regener's measurements from his balloon flights during the past summer are reliable, it appears that there is no detectable decrease in ionisation as the top of the atmosphere is approached. This would mean, in accord with the above reasoning, that no appreciable portion of the cosmic rays enters the earth's atmosphere in the form of photons.

[中文](#)

On the other hand, if the cosmic rays enter the atmosphere as electrons, they will produce photons just as cathode rays striking a target produce X-rays. Accordingly, at lower altitudes a mixture of electrons and photons will be present, and it may be expected that the photons will have the greater penetrating power. It is thus not impossible that the very penetrating cosmic rays observed by Millikan, Regener, and others at great depths under water may be such photons excited by the incoming electrons.

[中文](#)

Although we have discussed the problem as if the electrified particles which seem to constitute the cosmic rays are electrons, it will be

understood that the experiments that have been cited do not serve to distinguish between negatively and positively charged particles. The experiments are equally consistent with the view that the rays consist of protons or high speed α -particles. I find no way of reconciling the data, however, with the hypothesis that any considerable portion of the primary cosmic rays consist of photons. [中文](#)

(131, 713-715; 1933)

* Substance of an address presented at a symposium on cosmic rays, held by the American Physical Society at Atlantic City on December 30, 1932.

宇宙射线的性质*

阿瑟·康普顿

这是阿瑟·康普顿在美国物理学会的一次会议上就宇宙射线的地理分布以及它们的强度随高度变化的问题所作的演讲。与热带地区相比，宇宙射线的强度在温带和极区纬度上会有明显增强，这也许可以通过以下方式进行解释：如果初级宇宙射线是电子，它们以两个能量范围到达地球，那么高能粒子流几乎不会受到地球磁场的影响；而较低能段的粒子流会发生很大的偏转，因而根本无法到达赤道地区。这些数据表明构成宇宙射线的粒子不是光子，但不能区分是普通电子、“带正电的电子”、质子还是 α 粒子。今天我们知道大多数初级宇宙射线都是质子。

[英文](#)

能够直接说明宇宙射线性质的实验有三类。它们是：（1）博特-柯尔霍斯特的双计数器实验，可以用于比较穿过计数器的粒子的吸收和宇宙射线的吸收；（2）测量宇宙射线在地球上不同地区的相对强度，目的是了解地球磁场对其造成的影响；（3）研究宇宙射线强度随海拔高度的变化，根据宇宙射线是电子或是光子而采用不同的定律。

[英文](#)

[文](#)

（1）博特-柯尔霍斯特实验用于测量金块或铅块对高速带电粒子的吸收，带电粒子可在两个相邻计数室中产生同步脉冲。实验发现，这类吸收出奇地小，实际上与宇宙射线自身的吸收大致相同。

[英文](#)

对两者在吸收性质上相似的最简单的解释是假定宇宙射线就是高速运动的粒子。然而，还存在另外一种可能性，即认为初级宇宙射线是光子，当光子停止时会打出高速电子作为反冲电子，这些反冲电子以与初级宇宙射线本身大致相同的速率被吸收。理论计算表明，反冲电子被吸收的速度应该是产生它们的光子的吸收速度的5倍到10倍。这些计算结

果不是很准确，因为外推远远超过了被现有公式检验过的波长范围。由于这个原因，虽然宇宙射线和高速粒子具有相同的吸收系数并不足以排除这些粒子就是宇宙射线激发的反冲电子。不过，这仍然难以想象，公式的误差会大到5~10倍，以至于认为吸收系数的符合是由次级电子引起的。

[英文](#)

(2) 如果宇宙射线是从遥远太空进入地球大气的带电粒子，那么地球磁场应该会影响它们的地理分布。斯托默和爱泼斯坦曾对此进行过理论上的研究，最近勒梅特和瓦拉塔又大大完善了这一理论。他们的研究表明：对于能量小于 10^9 电子伏特的电子，它们在接近地球时只能到达纬度约 60° 以北的地方；对于能量大于约 5×10^{10} 电子伏特的电子，其地理分布不受地球磁场的影响；如果能量介于两者之间，入射电子的强度将会按照其能量分布随纬度而异。

[英文](#)

克莱在世界各地进行了宇宙射线相对强度的实验研究，他在爪哇与荷兰之间往返了好几次后发现赤道附近的强度总是比较低；密立根和卡梅伦也发现在玻利维亚湖附近的宇宙射线强度略低于加州山湖，而在帕萨迪纳与靠近北极的丘吉尔港之间的宇宙射线强度并无差别；博特和柯尔霍斯特带着一支计数管往返于汉堡（北纬 53° ）和斯匹次卑尔根群岛（北纬 81° ）之间，他们用误差较大的仪器没有检测到宇宙射线强度的变化；肯尼迪在格兰特的指导下，带了同样的装置从澳大利亚的阿德雷德到南极洲，同样没有测量到强度的变化；但科林在测量了斯堪的纳维亚半岛上从北纬 50° 到 70° 之间的宇宙射线强度后发现在大约北纬 55° 处有一个极大值。最近，霍夫曼总结了人们对这些测量结果的普遍看法：“迄今为止得到的结果从总体上说是负面的。大多数观测者认为，在实验误差范围内，宇宙射线的强度恒为一个常数，而那些发现强度确实存在差别的作者在公布结果时带有某种保留。”

[英文](#)

在过去的18个月内，麻省理工学院的贝内特教授、丹佛大学的斯特恩斯教授和我组织了一组有60余位物理学家参加的10次考察，我们试图在限定的时间内对宇宙射线的地理分布进行尽可能大范围的研究。图1中标出了分布在世界各地的81个观察站的位置，在这些位置我们都进行了测量。这些观察站在南北半球上基本上是平均分布的。从南纬 46° 延伸到北纬 78° ，从海平面一直到海拔约20,000英尺处（图2和图3）。当把

这些数据汇总在一起时，我们发现在温带和两极处的宇宙射线强度与赤道地区明显不同。在海平面上，强度差约为14%；在海拔2,000米处，约为22%；在海拔4,400米处，约为33%。在地磁纬度25°和40°之间，赤道地区宇宙射线强度与温带地区宇宙射线强度之间的差别会格外明显。

英文

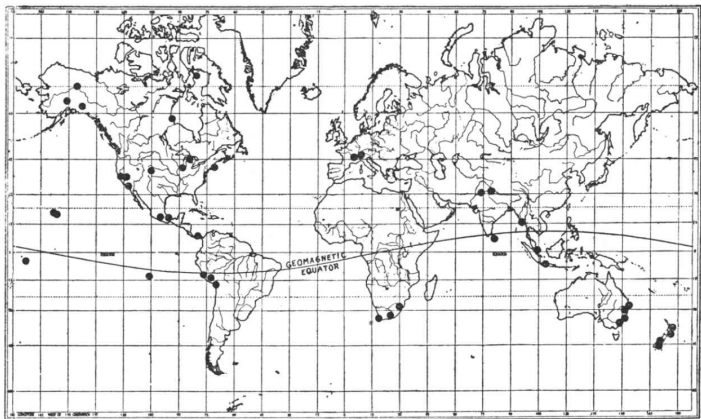


图1．考察队1932年在全球测量宇宙射线的主要站点分布图

英文

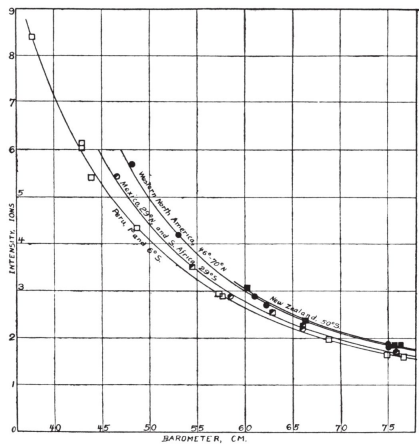


图2．典型的强度-气压曲线，这张图说明在世界上纬度不同的地区，宇宙射线的强度是不相同的。圆形，北半球；方块，南半球。

英文

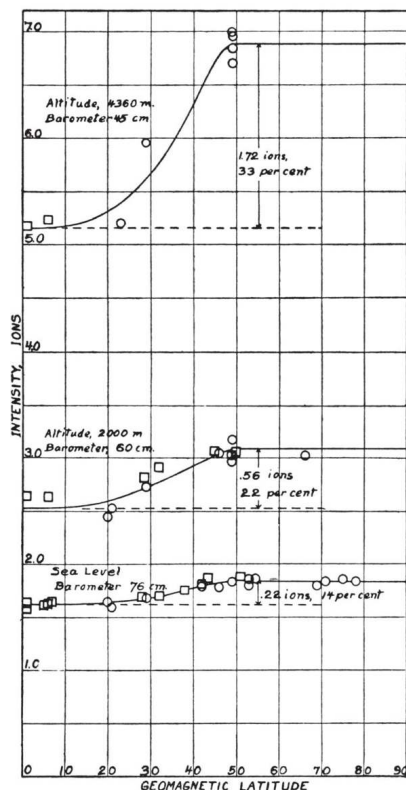


图3. 宇宙射线强度随地磁纬度的变化，包括在海拔高度不同的三个地点测量得到的结果。海拔越高，变化越明显。曲线是根据勒梅特-瓦拉塔的理论计算出来的。 [英文](#)

对这些实验数据与勒梅特和瓦拉塔理论的比较说明：如果进入地球大气层的宇宙射线由两个能量组的电子组成，则宇宙射线的分布就与人们预期的大体一致。其中的一组电子具有很高的能量，以至于基本不受地球磁场的影响。在温带地区的这组电子的能量占海平面处宇宙射线总辐射量的88%，这组电子是迄今为止的实验所关注的可以看作是光子的那一类。在海拔4,400米处该成分占总辐射量的75%。第二组成分穿透力稍差并表现为有相近能量的粒子，如果它们是电子，将具有约 7×10^9 电子伏特的能量。这些粒子可以进入地球的温带地区，但不能进入靠近赤道的地区。 [英文](#)

可以说，如果光子是组成宇宙射线的主体，那么即使是穿透性较差的那些宇宙射线所具有的能量也要远远高于由光子产生的反冲电子的能量。密立根认为，在海平面处对宇宙射线的吸收的测量表明：如果宇宙射线是光子，那么它们的能量就会达到 2×10^8 电子伏特数量级。这比使

温带和热带地区宇宙射线强度产生差异的电子的能量小很多（相差35倍），以至于我们似乎可以肯定到达地球的粒子不是反冲电子。另一方面，勒梅特-瓦拉塔的理论要求粒子的能量应达到 7×10^9 电子伏特，这意味着粒子的射程约为地球大气层厚度的三倍。这一点符合这样的事实，即这些射线可以穿透地球大气，但是有一定的困难。 [英文](#)

对宇宙射线地理分布的研究表明，宇宙射线中穿透力较差的部分起码会包含高速带电粒子。对于穿透性较强的成分，我们的结论是：如果它们是带电粒子，那么它们的能量就必须达到或超过 3×10^{10} 电子伏特。 [英文](#)

（3）在过去的两年内，人们已经进行了大量的实验以研究宇宙射线强度随海拔高度的变化。目前以雷格纳的探空气球和皮卡德的著名平流层气球到达的高度最高。我们在山上作实验时也特别关注这个研究课题。在图4中，我们对山上的实验数据与气球观测的结果进行了比较。这些数据表明：随着高度的增加，宇宙射线的强度很快上升，持续呈指数型增长直至15 km高度，从那儿起，当测试仪器接近大气层顶部时，强度达到极限值。 [英文](#)

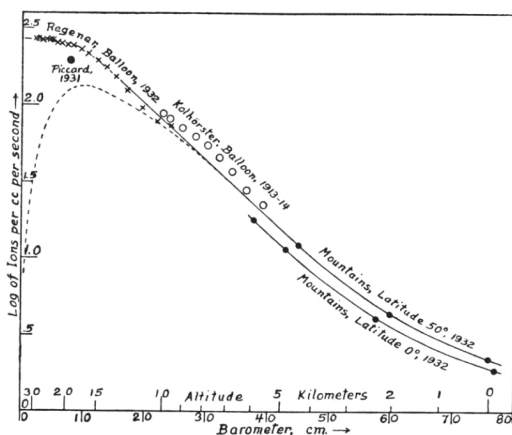


图4．综合气球实验和在山上所作的实验得到的宇宙射线强度随海拔高度的变化曲线。虚线是把宇宙射线看成光子后的预期值。 [英文](#)

假如我们把进入地球大气层的宇宙射线看作是光子，那么在太空中可能与这些光子相关联的次级电子都将因地球磁场的作用而偏离地球。因而我们应该有一束纯光子束进入大气层。在大气层表面，这些光子几

乎不会发生电离，因为电离直接由穿过计数室的次级电子产生。然而，这些次级电子只有在吸收了初始光子的能量后才能产生，它们在光子穿越大气层的厚度小于电子的射程时是不会达到其正常强度的。这意味着在海拔很高的地方，由进入地球的光子束引起的电离应该接近于零。当到达大气层某一深度处的宇宙射线有将近一半的量被吸收时，电离电流将达到极大值，而在不断接近海平面的过程中，宇宙射线的强度应逐渐减小。我们在高山上所作的实验与最近的气球实验结果相同，都没有发现在高海拔处出现极大值。这似乎可以排除从遥远太空进入地球大气层的宇宙射线是光子的可能性。

英文

另一方面，如果我们假设宇宙射线是从上方进入地球大气层的电子，我们应该能够很好地预期由现有实验得到的那类强度-高度曲线。众所周知，高速电子产生的每单位路径的电离在很宽的能量范围内几乎保持为一个常数。因此，如果一束这样的电子进入大气层，它们将产生几乎完全相同的电离直到这样一个深度，在这个深度上有数量相当可观的电子被空气阻止。如果初始的电子都是向下运动的，那么宇宙射线的电离发生快速下降的高度界线或范围将是非常明确的。然而，如果初始电子是从各个方向进入大气层的，则其中的某些电子会停止在大气层的上部。于是，假定宇宙射线是由外层空间进入地球大气层的电子所组成，实验的强度-高度曲线的总体特征就能很容易地得到解释。

英

文

如果雷格纳去年夏天用他的气球飞行实验得到的结果是可靠的，那么在接近大气层顶部时就不存在可探测的电离度下降。这意味着按照上述推理，在进入地球大气层的宇宙射线中，绝大部分都不是光子。

英文

另一方面，如果宇宙射线以电子形式进入大气层，则它们也会生成光子，就像轰击靶子的阴极射线能产生X射线一样。于是，在海拔高度较低的地方将出现电子和光子的混合，可以预期光子将有更强的穿透能力。而密立根、雷格纳和其他研究者在水下很深处观测到的穿透力超强的宇宙射线并非不可能存在，它们也许就是被入射电子所激发的光子。

英文

虽然我们推断组成宇宙射线的带电粒子可能是电子，但我们知道前面提到的那些实验都无法判断粒子带的是正电还是负电。这些实验结果同样可以用于说明宇宙射线是由质子或高速 α 粒子组成的。然而，如果假设初级宇宙射线的主要成分是光子，我认为上述数据就没办法得到解释了。 [英文](#)

（沈乃澂 翻译；马宇蓓 审稿）

* 这是在专题讨论会上的一篇有关宇宙射线的演讲稿，该讨论会是由美国物理学会于1932年12月30日在大西洋城举办的。

A Possible Property of the Positive Electron

W. Elsasser

The curious similarity of the neutron and proton, coupled with the discovery of the positron, suggested some intriguing possibilities for structures within the atomic nucleus. Some physicists had suggested that the proton might be a composite particle formed from a neutron and positron. Walter Elsasser suggests here that the hypothesis might also help explain recent discoveries about the proton's magnetic moment—a measure of its magnetic behaviour. He says the idea might account for why positrons seem to be found only in nuclei. Elsasser's suggestions were well motivated, but would soon be proven off the mark, especially by experiments showing the positron to have spin (a quantum property related to angular momentum) of $1/2$, just like the electron. [中文](#)

THE detection of the positive electron (called positron) by Blackett and Occhialini¹ and by Anderson² makes it very probable that the positron has a great importance in the building up of nuclei. Anderson² suggests that the proton may consist of a neutron and a positron. In favour of this hypothesis we may mention the experiments of Stern (still unpublished), who found that the magnetic momentum of the proton is three times greater than it should be if the proton were to behave like an elementary particle in Dirac's theory.

Following Heisenberg³, both the proton and the neutron obey Fermi statistics and have a half integral spin momentum. This leads at once to the conclusion that, if the hypothesis of Anderson is true, the positron should obey Bose statistics and have an integral spin momentum (0 or 1). If this view should be confirmed by other experimental evidence we should understand better why the positrons can only be found in nuclei; for, since positrons have symmetrical wave functions, they can always be placed in the deepest energy levels. It seems to be an advantage of the proposed hypothesis, that contrary to Dirac's theory of "holes"⁴ an essential asymmetry between positive and negative electricity is introduced into the laws describing the behaviour of elementary particles. Since the light-quanta also have whole number momenta, it seems that it may be a general rule, that symmetrical wave functions are combined with integral momenta and anti-symmetrical wave functions with half integral momenta. [中文](#)

(131, 764; 1933)

W. Elsasser: Physikalisches Institut, Technischen Hochschule, Zürich, April 25.

References:

1. *Proc. Roy. Soc.*, **139**, 699 (1933).
2. *Phys. Rev.* (March, 1933).
3. *Z. Phys.*, **77**, 1 (1932).
4. *Proc. Roy. Soc.*, **126**, 360 (1932).

正电子可能具有的性质

沃尔特·埃尔萨瑟

中子和质子的惊人相似以及正电子的发现使人们对原子核的内部结构浮想联翩。一些物理学家认为质子可能是由中子和正电子合成的。沃尔特·埃尔萨瑟在这篇文章中指出上述假说也许有助于解释最近的一项与质子磁矩有关的发现——一种对质子磁行为的测量。他说这个观点或许可以说明为什么正电子似乎只出现于原子核中。埃尔萨瑟的这种提法绝对不是空穴来风，但他的假设很快就被证明是错误的，实验证明正电子的自旋（一种与角动量相关的量子特性）为 $1/2$ ，和电子没有什么两样。 [英文](#)

布莱克特、奥基亚利尼^[1]和安德森^[2]探测到了带正电的电子（被人们称为正电子），这很有可能意味着正电子是原子核的重要组成部分。安德森^[2]指出，质子可能是由一个中子和一个正电子组成的。为了证明这个假说，我们要提到斯特恩的实验（尚未发表），他发现：根据狄拉克的理论，如果质子是基本粒子，那么它的磁矩应该是现在的3倍。按照海森堡^[3]的说法，质子和中子都遵循费米统计规律并具有半整数自旋动量。由此我们马上可以得到这样的结论：如果安德森的假说成立，那么正电子应该遵守玻色统计规律并且具有整数自旋动量（0或1）。如果这个观点能够被其他实验现象所证实，那么我们就可以更好地理解为什么正电子只出现在原子核当中；因为正电子具有对称的波函数，所以它们可以一直处在最低的能级上。这似乎支持了上面提出的假说，但却与狄拉克的“空穴”理论^[4]相反，狄拉克理论在描述基本粒子行为的物理规律中引入了正负电子之间重要的不对称性。由于光量子也具有整数自旋，看起来总的规律是：对称波函数与整数自旋动量并存，反对称波函数与半整数自旋动量并存。 [英文](#)

(王静 翻译；李军刚 审稿)

Positrons and Atomic Nuclei

G. W. Todd

Walter Elsasser had recently suggested that the proton might be a composite of neutron and positron, and that this hypothesis might help explain the positive charge of nuclei. Here George Todd criticizes that idea, and suggests another. He notes, however, that a particular transmutation of uranium can be understood in Elsasser's picture if the process involves the spontaneous creation of an electron and positron from nothing—a process that is now known to happen, although not here. Todd's proposed nuclear constitution leads to the conjecture that isotopes differ only by the number of neutrons in the nucleus, another prescient suggestion. [中文](#)

IN *Nature* of May 27, Dr. W. Elsasser offers evidence in favour of the suggestion that the proton consists of a neutron and a positron. Examining the question from a different point of view, I put forward the following as evidence against the suggestion. [中文](#)

If we allow that an atomic nucleus may contain α -particles, protons, neutrons, electrons and positrons, the number of possible structures for a nucleus of atomic mass P and atomic number Z increases rapidly with increase of P and Z , and for the heavy atoms it may run into hundreds. If we exclude the possibility of unattached electrons and positrons in the nucleus, then the structure becomes unique and is given by

$$\frac{1}{2}(Z - p) \alpha\text{-particles} + (P - 2Z + p) \text{ neutrons} + p \text{ protons} \quad (1)$$

where $p = 0$ or 1 , whichever value makes $\frac{1}{2}(Z - p)$ an integer. 中文

It is also possible to get a unique structure by excluding the possibility of unattached electrons but allowing the possibility of positrons. The structure is then

$$\frac{1}{2}(Z - p') \alpha\text{-particles} + (P - 2Z + 2p') \text{ neutrons} + p' \text{ positrons} \quad (2)$$

where again $p' = 0$ or 1 as before. This is practically the suggestion which Elsasser supports. 中文

Using these expressions, we can trace the changes which take place in the nuclei of radioactive elements during α - and β -ray transformations. The accompanying table shows a typical set of transformations.

	Nucleus from (1)	Nucleus from (2)	Radiation
Ur I	$46\alpha + 54n + 0p$	$46\alpha + 54n + 0p'$	$\left. \vphantom{\begin{matrix} \text{Ur I} \\ \text{Ur X}_1 \\ \text{Ur X}_2 \\ \text{Ur II} \\ \text{I}_0 \end{matrix}} \right\} \alpha$
↓ Ur X ₁	45 54 0	45 54 0	$\left. \vphantom{\begin{matrix} \text{Ur I} \\ \text{Ur X}_1 \\ \text{Ur X}_2 \\ \text{Ur II} \\ \text{I}_0 \end{matrix}} \right\} \beta$
↓ Ur X ₂	45 53 1	45 54 1	$\left. \vphantom{\begin{matrix} \text{Ur I} \\ \text{Ur X}_1 \\ \text{Ur X}_2 \\ \text{Ur II} \\ \text{I}_0 \end{matrix}} \right\} \beta$
↓ Ur II	46 50 0	46 50 0	$\left. \vphantom{\begin{matrix} \text{Ur I} \\ \text{Ur X}_1 \\ \text{Ur X}_2 \\ \text{Ur II} \\ \text{I}_0 \end{matrix}} \right\}$
↓ I ₀	45 50 0	45 50 0	

中文

The explanation of the α -ray changes is obvious. The β -ray changes in a radioactive series generally occur in pairs and the pair above shows changes identical with all other pairs of β -ray transformations. If the nuclear contents are expressed by (1), the changes take place in the following reasonable manner:—

$1n \rightarrow 1p + 1\beta$ the proton remaining in the nucleus,

and $3n + 1p \rightarrow 1\alpha + 1\beta$ the α -particle remaining in the nucleus.

On the other hand, if expression (2) gives the nuclear contents, then the changes which take place are

$0 \rightarrow 1p' + 1\beta$, a positron appearing in the nucleus,

and $4n + 1p' \rightarrow 1\alpha + 1\beta$, the α -particle remaining in the nucleus.

But where do the electron and positron come from in the first change, and how is the alteration in charge to be accounted for in the second change? [中文](#)

It is interesting to note that the expressions (1) and (2) give lower limits to the mass of an isotope. The minimum value from (1) is $P \geq 2Z - p$ and from (2) it is $P \geq 2Z - 2p'$. It will also be observed that isotopes only differ from each other in the number of neutrons in their nuclei. [中文](#)

(132, 65; 1933)

George W. Todd: Armstrong College, Newcastle-upon-Tyne, June 3.

正电子和原子核

乔治·托德

沃尔特·埃尔萨瑟最近指出质子可能是中子和正电子的合成物，而且这一假说很可能有助于解释原子核为什么带正电。在这篇文章中，乔治·托德反驳了这一观点，并提出了另外一个观点。不过托德指出：有一种特殊的铀嬗变也许可以用埃尔萨瑟的理论来解释，如果在这个过程中会凭空自发产生一个电子和正电子——现在我们知道这样的反应是存在的，虽然当时还不知道。由托德提出的核结构理论可以推出同位素之间的差别仅仅是原子核中的中子数不相同，这是托德的又一个真知灼见。 [英文](#)

在5月27日的《自然》杂志上，埃尔萨瑟博士提出证据证明质子是由一个中子和一个正电子组成的。我从不同的角度出发用以下证据来反驳这一观点。 [英文](#)

如果我们承认原子核有可能是由 α 粒子、质子、中子、电子和正电子组成的，那么对于一个原子质量为 P 、原子序数为 Z 的原子来说，它可能具有的结构个数将随着 P 和 Z 的增加急剧上升，而重原子可能具有的结构或许会达到数百种。如果我们排除原子核中存在独立正、负电子的可能性，那么就可以认为核结构只能有以下一种形式：

$$\frac{1}{2}(Z - p) \text{ 个 } \alpha \text{ 粒子} + (P - 2Z + p) \text{ 个中子} + p \text{ 个质子} \quad (1)$$

式中 p 取0或1，看哪一个值可以使 $\frac{1}{2}(Z - p)$ 为整数。 [英文](#)

如果只排除独立负电子，而允许独立正电子存在，也可以得到唯一的结构。此时原子核结构为：

$$\frac{1}{2}(Z - p') \text{ 个 } \alpha \text{ 粒子} + (P - 2Z + 2p') \text{ 个中子} + p' \text{ 个正电子} \quad (2)$$

和前面一样， p' 取0或1。事实上这就是埃尔萨瑟所支持的观点。[英文](#)

利用这些表达式，我们可以探索放射性元素的原子核在 α 和 β 射线衰变过程中发生的变化。下表中给出了一系列典型的衰变：

	式 (1) 中的原子核	式 (2) 中的原子核	辐射
Ur I	$46\alpha + 54n + 0p$	$46\alpha + 54n + 0p'$	} α
↓ Ur X ₁	45 54 0	45 54 0	
↓ Ur X ₂	45 53 1	45 54 1	} β
↓ Ur II	46 50 0	46 50 0	} β
↓ I ₀	45 50 0	45 50 0	}

[英文](#)

关于产生 α 射线的转变的解释是显而易见的。而产生 β 射线的转变在放射系中一般成对出现，上表中出现的那对表现出与所有其他 β 射线转变对相同的变化。如果原子核的构成可以表示为式（1），那么发生转变的合理方式应该是这样的：

$1n \rightarrow 1p + 1\beta$ ，质子留在原子核中； $3n + 1p \rightarrow 1\alpha + 1\beta$ ， α 粒子留在原子核中。

另一方面，如果原子核的构成可以表示为式（2），那么发生的转变则是：

$0 \rightarrow 1p' + 1\beta$ ，一个正电子出现在原子核中； $4n + 1p' \rightarrow 1\alpha + 1\beta$ ， α 粒子留在原子核中。

然而，在第一种转变中，电子和正电子从何而来？在第二个转变中，又如何解释电荷变化？[英文](#)

有趣的是，我们注意到式（1）和式（2）给出了同位素质量的下限。由式（1）推出的最小值为 $P \geq 2Z - p$ 而由式（2）推出的最小值为 $P \geq 2Z - 2p'$ 。我们还发现，同位素之间的区别仅仅在于其原子核中的中子数不相同。[英文](#)

Magnetic Moment of the Proton

I. Estermann *et al.*

Paul Dirac's theory of the electron predicted that it has a quantum-mechanical spin of $1/2$ and a magnetic moment equal to 1 Bohr magneton. As the theory would seem to apply to any elementary particle of spin $1/2$, physicists in the early 1930s expected the proton to behave similarly, having a magnetic moment smaller by the inverse ratio of their masses ($1/1,840$). But here Immanuel Estermann and colleagues announce a very surprising result: the magnetic moment of the proton is around 2.5 times larger than that. The result indicated that Dirac's theory failed in some important respects for the proton, and supplied the first experimental evidence that nuclear particles (nucleons) have internal structure. [中文](#)

THE spin of the electron has the value $\frac{1}{2} \cdot \frac{h}{2\pi}$, and its magnetic moment has the value $2 \frac{e}{m_e c} \cdot \frac{1}{2} \cdot \frac{h}{2\pi}$, or 1 Bohr magneton. The spin of the proton has the same value, $\frac{1}{2} \cdot \frac{h}{2\pi}$, as that of the electron. Thus for the magnetic moment of the proton the value $2 \frac{e}{m_p c} \cdot \frac{1}{2} \cdot \frac{h}{2\pi} = 1/1,840$ Bohr magneton = 1 nuclear magneton is to be expected. [中文](#)

So far as we know, the only method at present available for the determination of this moment is the deflection of a beam of hydrogen molecules in an inhomogeneous magnetic field (Stern-Gerlach experiment). In the hydrogen molecule, the spins of the two electrons are anti-parallel and cancel out. Thus the magnetic moment of the

molecule has two sources: (1) the rotation of the molecule as a whole, which is equivalent to the rotation of charged particles, and leads therefore to a magnetic moment as arising from a circular current; and (2) the magnetic moments of the two protons. [中文](#)

In the case of para-hydrogen, the spins of the two protons are anti-parallel, their magnetic moments cancel out, and only the rotational moment remains. At low temperatures (liquid air temperature), practically all the molecules are in the rotational quantum state 0 and therefore non-magnetic. This has been proved by experiment. At higher temperatures (for example, room temperature) a certain proportion of the molecules, which may be calculated from Boltzmann's law, are in higher rotational quantum states, mainly in the state 2. The deflection experiments with para-hydrogen at room temperature allow, therefore, the determination of the rotational moment, which has been found to be between 0.8 and 0.9 nuclear magnetons per unit quantum number. [中文](#)

In the case of ortho-hydrogen, the lowest rotational quantum state possible is the state 1. Therefore, even at the lowest temperatures, the rotational magnetic moment is superimposed on that due to the two protons with parallel spin. Since, however, the rotational moment is known from the experiments with pure para-hydrogen, the moment of the protons can be determined from deflection experiments with ortho-hydrogen, or with ordinary hydrogen consisting of 75 percent ortho- and 25 percent para-hydrogen. The value obtained is 5 nuclear magnetons for the two protons in the ortho-hydrogen molecule, that is, 2.5 (and not 1) nuclear magnetons for the proton. [中文](#)

This is a very striking result, but further experiments carried out with increased accuracy and over a wide range of experimental conditions (such as temperature, width of beam, etc.) have shown that it is correct within a limit of less than 10 percent. [中文](#)

A more detailed account of these experiments will appear in the *Zeitschrift für Physik*. [中文](#)

(**132**, 169-170; 1933)

I. Estermann, R. Frisch, O. Stern: Institut für physikalische Chemie, Hamburgischer Universität, June 19.

质子的磁矩

伊曼纽尔·埃斯特曼等

保罗·狄拉克的电子理论预言：电子的自旋量子数为 $1/2$ ，磁矩为1玻尔磁子。因为该理论似乎适用于所有自旋量子数为 $1/2$ 的基本粒子，所以20世纪30年代早期的物理学家们认为质子也有类似的特征，它的磁矩大小与其质量成反比，是电子磁矩的 $1/1,840$ 。但是，伊曼纽尔·埃斯特曼及其同事在这篇文章中报告了一个非常令人惊奇的结果：质子的磁矩大约是这一预计值的2.5倍。这一结果说明狄拉克的理论无法解释质子的一些重要特征，而且这也是证明核粒子（核子）具有内部结构的第一例实验证据。 [英文](#)

电子自旋角动量为 $\frac{1}{2} \cdot \frac{h}{2\pi}$ ，它的磁矩为 $2 \frac{e}{m_e c} \cdot \frac{1}{2} \cdot \frac{h}{2\pi}$ ，或者1玻尔磁子。质子的自旋角动量和电子具有相同的值 $\frac{1}{2} \cdot \frac{h}{2\pi}$ 。由此，我们猜想质子磁矩为 $2 \frac{e}{m_p c} \cdot \frac{1}{2} \cdot \frac{h}{2\pi} = 1/1,840$ 玻尔磁子 = 1核磁子。 [英文](#)

据我们所知，目前能够确定这一磁矩的唯一有效方法就是氢分子束在非均匀磁场中偏转的实验（斯特恩-盖拉赫实验）。在氢分子中，两个电子的自旋是反平行的，所以互相抵消了。这样，分子磁矩就有两种来源：（1）分子作为一个整体的旋转，这等价于带电粒子的旋转，因此可以产生由环形电流引发的磁矩；（2）两个质子的磁矩。 [英文](#)

在仲氢分子中，两个质子的自旋是反平行的，因此它们的磁矩相互抵消，只有转动力矩存在。在低温下（液化空气温度），几乎所有的分子都处于转动量子态为0的状态，所以是非磁性的。这一点已经被实验所证实。在较高的温度下（例如室温），可以用玻尔兹曼定律算出有一定比例的分子处于更高的转动量子态上，以2态为主。因此，室温下仲氢分子的偏转实验可以用来确定其转动力矩，我们已经得到的转动力矩

为每单位量子数0.8到0.9核磁子之间。 [英文](#)

在正氢中，可能存在的最低转动量子态是1态。因此，即便是在最低的温度下，由于两个质子的自旋平行，转动磁矩也会叠加。然而，因为转动力矩已经由纯仲氢的实验测得，所以质子的磁矩可以从正氢或者从含75%正氢和25%仲氢的普通氢的偏转实验中得到。结果是，正氢分子中两个质子的磁矩是5核磁子，也就是说，质子的磁矩是2.5（而不是1）核磁子。 [英文](#)

这是一个非常惊人的结果，但我们在后来的实验中提高了精度，并尝试了各种不同的条件（例如，不同温度，不同分子束宽度等），实验仍表明，这个结果的误差小于10%。 [英文](#)

我们将在《物理杂志》上发表有关这个实验的更多细节。 [英文](#)

（王静 翻译；赵见高 审稿）

Interaction between Cosmic Rays and Matter

B. Rossi

Italian physicist Bruno Rossi had recently shown that cosmic rays passing through matter often generate secondary particles. He had developed a sensitive technique to investigate the secondary “particle showers” by detecting the near-simultaneous passage of particles at three different detectors. Here he reports that showers seems to be more abundant in materials of higher atomic number, and that the particles penetrate lead for shorter distances than primary cosmic rays. Rossi’s technique spurred the further development of “coincidence-detection” devices for high-energy and nuclear physics. Rossi himself later showed that cosmic rays near the Earth’s surface have two components. The first component was ultimately identified as electrons and photons, the second with a new type of particle called the muon. [中文](#)

LAST year I showed by means of a coincidence method that a secondary corpuscular radiation is generated when cosmic rays pass through matter¹. From the beautiful experiments of Blackett and Occhialini we know now that these secondary particles are produced in so-called “showers”. This can also be shown by the method of coincidences; moreover, if a coincidence is observed between counters arranged in a triangle, we may conclude with a high degree of

certainty that we have to do with a shower originating from a point in the neighbourhood of the counters². The method of triple coincidences therefore offers a very useful means for investigating the frequency of occurrence of the showers. [中文](#)

Up to the present, the following results have been obtained:

(1) The showers occur more frequently in elements of high atomic number; the ratio of the numbers of coincidences caused by thin layers of lead, iron, aluminium of the same weight per cm.² is 4:2:1 approximately³.

(2) The number of showers emerging from a layer of lead, as a function of the thickness of this layer, increases at first, reaches a maximum at a thickness of about 20 gm./cm.² and then decreases very rapidly; at 100 gm./cm.², for example, the frequency of the coincidences is less than one half of the maximum value. We conclude that the radiation which causes the showers has a mean range of a few centimetres in lead. It follows that this radiation cannot be identical with the primary cosmic rays.

(3) When the thickness of the layer is further increased, the frequency of the emerging showers decreases very slowly. The most probable hypothesis to explain this seems to be to assume that a further production of the rays which cause the showers takes place in the layer; these rays are therefore to be regarded as a secondary radiation of the primary cosmic rays, the equilibrium value of which is roughly three to four times greater in air than in lead.

(4) The shower-producing rays are more readily absorbed by elements of higher atomic number. When 24.5 gm./cm.² of lead is placed over the counters, 70 ± 3 coincidences per hour are observed; this number was reduced to 36.7 ± 1.4 by a further sheet of lead of 39 gm./cm.² on top of the first one but only to 52.3 ± 1.7 by a sheet of aluminium of the same weight per cm.² and in the same position. From this and

from (1) we conclude that the absorption of these secondary rays by an element and the number of showers which they produce depend in the same way on the atomic number. Thus it seems that the production of showers must be the main reason for their absorption. This is in agreement with the consideration that these rays should have an energy of at least some milliards of electron-volts, which could not be absorbed by a few centimetres of lead in the ordinary way.

(5) That the equilibrium value of the secondary radiation is lower in elements of high atomic number may be explained by their greater absorption, if we assume that the rate of production is roughly the same in all elements; which seems plausible from the experiments on the absorption of the primary rays. 中文

(132, 173-174; 1933)

Bruno Rossi: Physical Institute, University of Padova, Italy, July 3.

References:

1. Rossi, B., *Phys. Z.*, **33**, 304 (1932).
2. Rossi, B., *Atti. R. Acad. Naz. Lincei* (in the press).
3. Rossi, B., *Z. Phys.*, **82**, 151 (1933).

宇宙射线与物质之间的相互作用

布鲁诺·罗西

意大利物理学家布鲁诺·罗西前不久指出，宇宙射线在穿过物质时经常会产生次级粒子。他还发展了一种很灵敏的技术，通过探测三个不同的探测器上几乎同时达到的粒子流来研究这些次级“粒子簇射”。在这篇文章中他指出，在较高原子数元素的物质中，簇射会更多，并且与初级宇宙射线相比，次级粒子在铅中的穿透距离更短。罗西的技术促进了高能物理和核物理学中所使用的“符合探测”装置的进一步发展。罗西本人后来发现，地球表面附近的宇宙射线中存在两种组分，其中一种组分最终被确定是电子和光子，而另一种组分中包含一种被称为 μ 介子的新型粒子。 [英文](#)

去年，我用符合法证明了当宇宙射线穿过物质时会产生次级微粒辐射^[1]。现在，我们根据布莱克特和奥基亚利尼的精巧实验得知这些次级粒子是在所谓的“簇射”中产生的。这一点也可以用符合法来证明；此外，如果我们看到排列成三角形的计数器同时触发信号，那么就可以非常确定地得出以下结论：这种符合一定与这些计数器附近某一点上产生的簇射有关^[2]。因此，三重符合法对于研究簇射出现的频率是非常有效的。 [英文](#)

到目前为止，我们已经得到了以下这些结论：

（1）簇射在高原子数元素的物质中出现得更频繁；由每平方厘米重量相同的铅、铁、铝薄层引发的符合次数比率大约为4:2:1^[3]。

（2）铅层中产生的簇射数是该层厚度的函数，随着厚度的增加，簇射数一开始增加，在厚度约为20克/平方厘米时达到最大值，然后迅速减少；例如，当厚度为100克/平方厘米时，符合出现的频率不到最大

值的一半。我们的结论是：引发簇射的辐射在铅中的平均射程为几个厘米。由此可以肯定这种辐射不同于初级宇宙射线。

(3) 当薄层的厚度继续增加时，簇射出现的频率减小得非常慢。对这一现象最有可能的解释是假设引起簇射的射线是在层中进一步产生的；因而这些射线被认为是初级宇宙射线的次级辐射，它们在空气中的平衡常数是在铅中的3~4倍左右。

(4) 产生簇射的射线更容易被较高原子数的元素所吸收。当把24.5克/平方厘米的铅置于计数器上时，每小时可以观察到 70 ± 3 次符合；如果在原有铅层上再放置一层39克/平方厘米的铅，这个值就会减小到 36.7 ± 1.4 ，但当在同一位置放置每平方厘米重量相同的铝层时，这个值只减小到了 52.3 ± 1.7 。根据这一现象和(1)，我们可以得出这样的结论：元素对次级射线的吸收以及次级射线产生的簇射数以同样的方式取决于原子数的大小。由此看来簇射的产生一定是射线吸收的主要原因。这与认为这些射线至少具有数十亿电子伏特的能量，在通常情况下不可能被几厘米厚的铅层吸收的论点是一致的。

(5) 如果我们假设簇射在所有元素中的产生率大致相同，那么就可以把原子数高的元素次级辐射平衡常数较小的原因归于原子数高的元素具有较强的吸收；从初级射线吸收实验的结果来看，这样的解释看上去是合理的。

英文

(王静 翻译；刘纯 审稿)

Disintegration of Light Atomic Nuclei by the Capture of Fast Neutrons

W. D. Harkins *et al.*

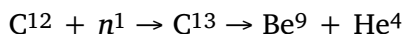
Observations of nuclear disintegration induced by neutrons provoked suspicions that such nuclear processes play a role in the Sun and other stars. Here William Draper Harkins and colleagues report experiments on the disintegration of nitrogen and several other nuclei by high-energy neutrons. They noticed that the incident neutrons must possess a certain threshold energy, which is converted to a mass increase in the product particles. For nitrogen this threshold is equivalent to the energy of particles in a gas with average temperature of about 10^{10} K. A small fraction of particles in a gas at typical solar temperatures would also have such velocities, suggesting that light atoms may undergo such disintegrations in stars. [中文](#)

ABOUT thirteen disintegrations of neon nuclei have been obtained in 3,200 pairs, and approximately 100 disintegrations of nitrogen nuclei in 7,600 pairs of photographs of a Wilson chamber through which neutrons were passing. The source of the neutrons consisted of beryllium powder intimately ground with a mixture of mesothorium and thorium-X. The neutron source used was on the average more powerful in the experiments with neon than with nitrogen. If all the

factors are taken into account, it is found that with identical atomic concentrations of neon and of nitrogen in the chamber, the neon nuclei are disintegrated much less often than those of nitrogen. 中文

The average energies of the neutrons which have been found to disintegrate light nuclei are, in millions of electron volts, 5.8 for nitrogen, 7.0 for oxygen, and 11.6 for neon. Here the value for oxygen is taken from the work of Feather. The mass data indicate that the energy needed to supply mass increases in just this order, and is respectively -1.4×10^6 , 0 and $+2 \times 10^6$ electron volts, if the mass of the neutron is assumed to be that given by Chadwick, 1.0067, which is probably too high. Obviously the value assumed does not affect the differences between the energy values. 中文

In a gas, ethylene, which consists of hydrogen and carbon, three disintegrations were obtained in 3,200 pairs of photographs. If carbon (12) is disintegrated by capture of the neutron the reaction is



$$12.0036 + 1.0067 \rightarrow 9.0155 + 4.00216$$

or, if the mass assumed for the neutron is correct, $\Delta m = 0.0074$, which is equivalent to 6.9×10^6 electron volts. 中文

This corresponds to a velocity of 3.6×10^9 cm. per sec., so only neutrons of a velocity higher than this should be effective in disintegrating carbon of mass 12. The smallness of the yield of disintegrations which we have obtained with carbon is thus to be expected, especially since probably less than one-fifth of the neutrons have velocities higher than this. 中文

A remarkable relation which has been found to hold without exception is: in disintegrations by capture of a neutron the kinetic

energy almost always decreases, is sometimes conserved, but in no case increases. [中文](#)

It has been pointed out previously by Harkins that the values for the energy which disappears suggest definite energy values for the γ -rays into which this energy is converted, but the accuracy of the work is not yet sufficient to prove that this is true. [中文](#)

It may be assumed that the neutrons in the stars are scattered by the atomic nuclei and thus take part in the temperature distribution of velocities of the atoms. If the neutrons of higher velocity are captured much more often than those of lower velocity, the distribution will be affected. Our experiments give no information concerning the capture of neutrons without disintegration, but only for those cases in which the capture is revealed by the accompanying disintegration. [中文](#)

It is of interest in this connexion to consider the minimum energy of the neutron which has been found to give a disintegration. The values, in millions of electron volts, are 1.9 for nitrogen, and 7.8 for neon. The corresponding maximum values are 16.0 and 14.5, the lower maximum for neon being due to the smallness of the number of disintegrations which have been obtained in this gas. An energy of 1.9×10^6 corresponds to a mean temperature of the order of 10^{10} degrees, but at 10^8 degrees a considerable number of neutrons should have this energy, and a moderate number even at 10^7 , so it is not unreasonable to suppose that nitrogen nuclei are disintegrated by this process in the stars. [中文](#)

A part of this work was presented by Harkins on June 23 at a symposium on nuclear disintegration under the auspices of the Century of Progress Exposition, Chicago. Other papers were presented by Cockcroft, Lawrence and Tuve, and a general discussion of the theory was given by Bohr. [中文](#)

轻核俘获快中子产生的核衰变

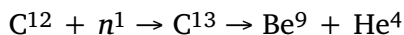
威廉·德雷珀·哈金斯等

在观察到由中子引发的核衰变之后，人们猜测这样的反应可能会存在于太阳和其他恒星之中。在本文中，威廉·德雷珀·哈金斯和他的同事们报告了氮及其他原子核在快中子诱发下产生的衰变。他们发现入射中子必定有一个能量阈值，这个能量转化为反应产物粒子的质量增加。对于氮来说，这一阈值等价于粒子处于气体平均温度约为 10^{10} K时的能量。在太阳所处的温度下，气体中有一小部分粒子可以达到这样的速度，这说明恒星中的轻原子可能确实经历了这样的核衰变过程。 [英文](#)

观察中子穿过威尔逊云室所得到的照片，在3,200对氦核照片中得到了大约13次核衰变，而在7,600对氮核照片中则大概得到了100次核衰变。中子源是由钨粉末与新钍和钍-X的混合物充分研磨而成。平均而言，所使用中的子源在用氦进行实验时比用氮进行实验时强。如果考虑到所有的因素，我们就会发现当云室中的氦和氮具有相同的原子浓度时，氦核的衰变数通常会显著地少于氮核的衰变数。 [英文](#)

我们已经知道能使轻核发生衰变的中子的平均能量，若以百万电子伏特计，对于氮是5.8，对于氧是7.0，对于氦则是11.6。上述关于氧的数值是从费瑟的研究成果中得到的。质量数据表明：如果假定中子的质量等于查德威克给出的数值1.0067——这个值有可能偏高，那么供给反应产物粒子的质量增加所需的能量也恰好按这个顺序增加，分别为 -1.4×10^6 ，0和 $+2 \times 10^6$ 电子伏特。显然，假定的中子质量大小并不影响能量之间的差值。 [英文](#)

在由氢和碳组成的乙烯气体中，我们从3,200对云室照片中得到了3次衰变。如果碳（12）通过捕获中子而发生了衰变，则其反应为：



$$12.0036 + 1.0067 \rightarrow 9.0155 + 4.00216$$

也就是说，如果我们采用的中子质量是正确的，则 $\Delta m = 0.0074$ ，相当于 6.9×10^6 电子伏特。 [英文](#)

这对应于 3.6×10^9 cm/s的速度，所以只有速度超过这个值的中子才能有效地使质量为12的碳发生核衰变。所以我们可以理解为什么碳的衰变率比较低了，因为很可能只有不到五分之一的中子具有高于这个值的速度。 [英文](#)

一个至今没有出现例外情况的、值得注意的关系是：在俘获中子的核衰变过程中，动能几乎总是在减少，有时候会保持恒定，但绝不会增加。 [英文](#)

哈金斯以前曾指出：反应中消失的能量值就是由该能量转变成的 γ 射线的确切能量值，但是目前该项实验的精确度还不足以证明这种说法是正确的。 [英文](#)

我们也许可以假设恒星中的中子被原子核散射，因而参与了原子速度的温度分布。如果具有较高速度的中子比具有较低速度的中子更容易被俘获，那么上述分布情况就会受到影响。我们的实验没有给出与未引起核衰变的中子俘获相关的信息，而只涉及了那些伴随着核衰变的俘获现象。 [英文](#)

与此相关，我们有兴趣了解目前已发现的能导致核衰变的中子所具有的最小能量。以百万电子伏特计，该值对于氮是1.9，对于氦是7.8。与两者对应的最大值分别为16.0和14.5，氦的最大值偏低是因为在这种气体中得到的核衰变数较少。当平均温度的数量级达到 10^{10} 度时，对应的能量值为 1.9×10^6 ，不过在 10^8 度时就会有相当数量的中子具有这一能量，甚至在 10^7 度时就会有一些，所以假定在恒星中氮核可以通过这一过程实现核衰变没有什么不合理。 [英文](#)

哈金斯于6月23日在芝加哥世纪进步博览会主办的关于核衰变的研讨会上介绍了该项研究中的一部分内容。考克饶夫、劳伦斯和图夫宣读

了另外一些论文，对理论进行全面阐述的则是玻尔。 [英文](#)

（王耀杨 翻译；朱永生 审稿）

Extremely Low Temperatures

W. J. de Haas

Physicist Wander Johannes de Haas of the University of Leiden reports here on recent experiments reaching extremely low temperatures using the method of “adiabatic demagnetisation”. In this method, a material magnetised by being held in a strong magnetic field can grow much colder if the field is abruptly removed. De Haas describes experiments with cerium fluoride. Preliminary tests were able to achieve a temperature of 0.27 K, and de Haas’s team had more recently reduced this to 0.085 K. With the same apparatus, de Haas suggests, much lower temperatures should be possible. Given these extremes, he notes, current methods for measuring temperatures have reached their limits, and further progress will require new thermometers suited to very low temperatures. [中文](#)

IN 1926 Debye pointed out that temperature must decrease when a magnetised body is demagnetised adiabatically. Giauque made the same remark in 1927; and still earlier the same idea was expressed by Langevin for oxygen. Debye calculated the predicted effect for the case of gadolinium sulphate. His calculation was based upon the following considerations: a magnetisable body contains a great number of small elementary magnets. When such a body is magnetised these magnets are directed. The part of the entropy belonging to this order is decreased and, the process being supposed

isentropic, the part of the entropy connected with the statistical movement must necessarily increase. When, on the contrary, the disorder of the elementary magnets is increased by demagnetisation, the part of the entropy connected with the magnetisation is increased and the part belonging to the statistical movement is decreased, so that the body is cooled down. 中文

If we wish to obtain easily seen results, the following points require special attention: (1) the elementary magnets shall not exert a directing influence upon each other (no ferromagnetic body); (2) the elementary magnets shall have a moment as large as possible, subject to the restriction of (1); (3) at low temperatures the effect will be greatest, as here the part of the entropy belonging to the magnetisation becomes comparable with the other part, while at the same time the order strongly increases. 中文

The condition to be fulfilled by the experimental arrangement in order to obtain extremely low temperatures is that the exchange of heat with the surroundings both by radiation and by connexion is cut down. In our experiments this condition is satisfied. The substance that is cooled down is at the same time used as a thermometer. 中文

The experiments were made with cerous fluoride (a weakly paramagnetic salt of one of the rare earths) as suggested by Prof. Kramers, of Utrecht (see "Leipziger Vorträge", 1933). Fig. 1 very diagrammatically represents the experimental arrangement. The rod *A* is fixed to a balance. It carries a small Dewar flask, which contains a small tube filled with cerous fluoride and suspended by a central carrier *B*. The whole apparatus is placed between the poles of the large electro-magnet of the Kamerlingh Onnes Laboratory in such a way that the salt occupies the spot of maximum $H \cdot dH/dx$ (x =vertical co-ordinate). The lower extremity of the rod *A* together with the small Dewar flask is surrounded by liquid helium boiling at 1.26°K. The

thermal insulation of the cerous fluoride is so good, that after 4–5 hours only a very small quantity of salt of exceedingly low heat capacity (the latter is inversely proportional to T^3) is cooled down to 1.26°K. 中文

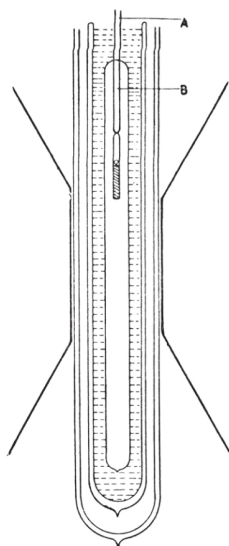


Fig. 1 中文

We know that finally this temperature has been reached, because the salt is the indicator of its own temperature. This paramagnetic body is drawn into the field (31 k. gauss) by a force $K = M \cdot dH/dx$, where M is the total moment of the body. As $M = \varphi(H, T)$ and as H remains constant, we easily see, by measuring K , when T has become constant.

中文

As soon as this is the case the body is demagnetised by lowering the field to 2.7 k. gauss in the first experiments, to 1,000 or 500 gauss in later experiments. 中文

In this weak field the force K is measured as a function of the time. In this way we obtain a curve as shown in Fig. 2. 中文

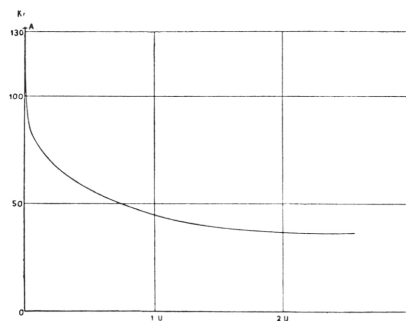


Fig. 2 中文

The point A on the curve corresponds to the force at the lowest temperature, while the asymptote after a long time corresponds to the force at 1.26°K. The steep fall of the curve in the beginning is due to the fact that in the vacuum of the small Dewar flask a trace of helium (10^{-7} mm.) has been left intentionally for thermal contact. This helium gas is condensed under development of the heat of condensation. When the pressure of the helium gas is still lower, the curve has a different form and heating up with the time goes extremely slowly. The cold has been caught in a trap. The vacuum becomes practically absolute and heat is no longer transmitted. 中文

The forces are directly proportional to the moments and the only thing we have to find out is to which temperatures these moments correspond. The connexion between temperature and moment has been determined between 7.2°K. and 1.3°K. The curve representing this connexion was extrapolated linearly, though this gives a stronger increase of the moment than the curve itself does. That is why we can only give an upper limit of the temperature reached. 中文

The first experiments were made in March and April of this year with cerium fluoride and gave as the upper temperature limit 0.27°K. More recent experiments with dysprosium ethyl sulphate gave the upper limit 0.17°K. Finally, the experiments of July last made with cerium ethyl sulphate gave as the upper temperature limit 0.085°K. 中文

It is possible that with the same experimental arrangement much lower temperatures can be reached. The choice of the right substance will decide further results. I am convinced that with the above-described arrangement the theoretical limit can be reached. 中文

Up to the present, the lowest temperatures had been reached with the aid of liquid helium, boiling under very low pressures. The results of this method evidently depend upon the capacity of the pumps used and upon the perfection of the thermal insulation. 中文

With this method Kamerlingh Onnes reached in October, 1921, a temperature of 0.82°K . Keesom worked with diffusion pumps of a capacity fifteen times higher than that of the pumps Kamerlingh Onnes had. In 1929 he reached a temperature of 0.71°K . It is, however, difficult to proceed much further in this way. 中文

The conception of temperature is based upon the properties of the ideal gas. The temperature is determined with the aid of the helium thermometer (several corrections being applied). At the extremely low temperatures reached recently no gas thermometric measurement of the temperature is possible, so far as I can see. 中文

A thermometric scale based upon another process must be fitted to the absolute temperature scale; only a magnetic scale can be used for this purpose. 中文

Just as was done in gas thermometry, we shall have to find some substances, which within a considerable range of temperature show the same behaviour; a highly developed theory will then enable us to fix the temperature with the same accuracy by means of magnetic thermometry as by the use of gas thermometric methods. 中文

A reservation must be made, however, for the case that at very low temperatures the substances used might become ferro-magnetic or might show a new kind of ferro-magnetism. In this case little might be

said about the temperature. 中文

Another great difficulty is this: if by means of the magnetic method we wish to cool down other substances, the question of the thermal contact becomes urgent. The radiation is negligible, and also the vapour pressure of the helium becomes so small that thermal contact by means of gaseous helium can scarcely be considered. 中文

The experiments were made in collaboration with Dr. E. C. Wiersma, conservator of the Laboratory, to whom I express my warmest thanks for his help and for many suggestions. To Prof. H. A. Kramers of Utrecht I am indebted for his valuable theoretical assistance. 中文

(132, 372-373; 1933)

极低温

万德·约翰尼斯·德哈斯

荷兰莱顿大学的物理学家万德·约翰尼斯·德哈斯在下文中描述了他最近利用“绝热退磁”法达到极低温的实验。在这一方法中，先使一种材料在强磁场中被磁化，然后突然去除磁场，则材料会变得更冷。德哈斯介绍了他用氟化铈所作的实验。最初实验，温度只能达到 0.27 K，近来德哈斯领导的团队已经把温度降低到 0.085 K。德哈斯认为，用这一装置还可以得到更低的温度。在给出这些极限值之后他注意到，在这么低的温度之下，当前的测温手段都已经达到了它们的极限，下一步的进展要求适用于很低温度的温度计。 [英文](#)

1926年德拜指出，被磁化了的物体在绝热去磁时其温度一定会降低。吉奥克在1927年也提出了同样的观点；在更早之前，朗之万就曾提到氧有这样的性质。德拜以硫酸钆为例，对预期效应进行了计算。他的计算基于以下几个原则：一种可磁化的物体中含有大量小的单元磁体。当该物体被磁化时，这些磁体会发生定向排列。属于这一有序的那部分熵会减少，而该过程被认为是一个等熵的过程，与统计运动相关的那部分熵就一定会增加。反过来，当单元磁体的无序度由于退磁而增加时，与磁化有关的那部分熵就会增加，而与统计运动相关的那部分熵则会减少，从而使物体的温度降低。 [英文](#)

如果我们想得到显而易见的结果，就需要特别注意以下几点：

- (1) 单元磁体彼此之间不应该存在直接的相互作用（非铁磁体）；
- (2) 由于第(1)点的限制，单元磁体应具有尽可能大的磁矩；
- (3) 这种效应在低温时将达到最大，因为这时与磁化对应的那部分熵变得与另一部分熵大小差不多，与此同时，有序剧烈地增加。 [英文](#)

为了获得极低的温度，在实验中必须保证完全切断与环境之间通过

辐射或传导而进行的热交换。在我们的实验中这个条件是满足的。被冷却的物质同时也被用作温度计。 [英文](#)

实验是用乌得勒支大学的克拉默斯教授建议的三氟化铈（一种稀土弱顺磁盐）（参见《莱比锡演讲》，1933年）进行的。图1简单画出了我们所用的实验装置。棒A固定在一平衡物上。它连着一个小的细长杜瓦瓶，杜瓦瓶中的小试管装有三氟化铈，小试管由中间导管B悬挂着。整个装置被置于卡默林·昂内斯实验室的大型电磁铁的两磁极之间，并确保顺磁盐样品处于 $H \cdot dH/dx$ 最大值的位置（ x 为垂直坐标）。棒A的最下端以及整个小杜瓦瓶都浸没在沸点为1.26 K的液氮中。三氟化铈的热绝缘非常好，以至于4~5个小时之后只有极少量的这种具有极低热容量（与 T^3 成反比）的盐被冷却到了1.26 K。 [英文](#)

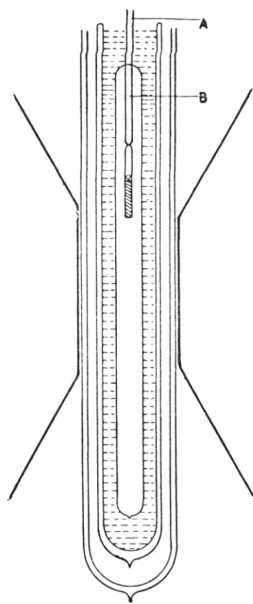


图1 [英文](#)

由于这种盐是其自身温度的指示器，我们知道最终被冷却到了1.26 K。力 $K = M \cdot dH/dx$ 将顺磁体吸入磁场中（强度为31,000高斯），其中 M 是顺磁体的总磁矩。由于 $M = \varphi(H, T)$ ，且 H 是保持不变的，我们很容易通过测量 K 而看出 T 是何时变为恒定的。 [英文](#)

一旦满足了以上所说的情况，就通过降低磁场给顺磁体退磁，在头

几次实验中把磁场降至2,700高斯，而在以后的实验中降到了1,000或500高斯。 [英文](#)

在这种弱场中，测量了作为时间的函数的力 K 。这样，我们得到了图2所示的曲线。 [英文](#)

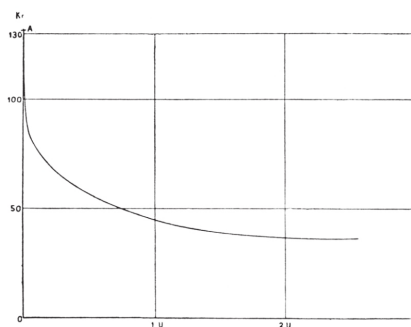


图2 [英文](#)

曲线上的A点对应于最低温度时力的值，而长时间后的渐近线趋近于温度为1.26 K时力的值。曲线在开始时急剧下降是因为在抽成真空的小杜瓦瓶中，为了保证热接触而有意留下了少量的氦（ 10^{-7} mm）。这些氦气在放出凝聚热的过程中被凝聚。当氦气的压强更低时，曲线具有不同的形式，随时间而升温的速度十分缓慢。低温被维持在阱里。这时的真空实际上变成绝对真空，而且不再有热传输了。 [英文](#)

力正比于磁矩，因而我们唯一需要确定的是这些磁矩对应什么温度。在7.2 K到1.3 K之间，温度与磁矩的关系已经确定了。代表这一关系的曲线被线性外推，尽管这样做给出的磁矩随时间增加的幅度比实际曲线上增加的幅度还要大一些。这就是为什么我们只能给出所能达到的温度的上限的原因。 [英文](#)

最初的实验是在今年3月和4月用氟化铈进行的，得到的温度上限为0.27 K。较近期实验是用硫酸乙基铈进行的，给出的温度上限为0.17 K。最后一次实验是在今年7月用硫酸乙基铈进行的，给出的温度上限为0.085 K。 [英文](#)

用同样的实验装置有可能达到更低的温度。正确地选用顺磁物质将决定未来的结果。我确信用上述装置可以达到理论的极限。 [英文](#)

目前人们已经可以用在极低压强下沸腾的液氦达到最低的温度了。这一方法的最终结果很明显地取决于所用泵的排量，以及热绝缘的理想程度。 [英文](#)

1921年10月，卡默林·昂内斯利用这种方法达到了0.82 K的低温。基桑使用的扩散泵排量是卡默林·昂内斯所用的15倍。他在1929年实现了0.71 K的低温。不过，这个方向的研究已经很难再有更大的进展了。

[英文](#)

温度的概念是以理想气体的性质为基础的。我们是借助氦温度计（已进行过多次校正）来测定温度的。在我看来，在最近所达到的极低温度下，没有一种气体温度计的测温方法是可行的。 [英文](#)

基于其他过程的温标必须拟合到绝对温标；为此目的，只有磁学标度是可用的。 [英文](#)

正如在气体测温术所做的那样，我们必须找到某种在相当宽的温度范围内呈现同一行为的物质；然后，已经高度发展了的理论将使我们能够用磁测温术得到与气体测温法同样精确的温度。 [英文](#)

但是我们必须有所保留，因为在极低的温度下，所使用的物质可能会变成铁磁性或者表现出新型的铁磁性。在这种情况下，就很难谈什么温度了。 [英文](#)

另一个巨大的困难是：如果我们希望利用磁学方法来冷却其他物质，那么热接触就变成了非常紧迫的问题。辐射是可忽略的，而且氦的蒸汽压也变得非常小，以至于几乎不能考虑通过气态氦进行热接触。

[英文](#)

实验是在实验室管理员威尔斯玛博士的协作下进行的，我要对他的帮助和诸多建议表示最真诚的谢意。我还要感谢乌得勒支的克拉默斯教授在理论方面所提供的有价值的帮助。 [英文](#)

（王耀杨 翻译；陶宏杰 审稿）

Recent Developments in Television*

A. Church

Companies in Europe and America were racing to develop the technology for television. As Archibald Church notes in this review, the scepticism widely expressed in 1926 after John Baird first demonstrated blurred and flickering television images was now being replaced by feverish excitement. In 1932, the Derby horse race had been televised and projected to a live audience in London, and the British Broadcasting Corporation had installed transmission equipment from Baird Television Ltd. Now engineers were developing improved displays based on cathode rays projected on fluorescent screens, and live broadcast was approaching feasibility. A finer screen resolution was needed, however and it was becoming necessary to allocate place in the broadcast spectrum for television signals. 中

文

ALL development of the art of television is recent. It is less than ten years since John Baird first obtained televised images of simple stationary objects such as a Maltese cross. He first demonstrated “real” television, the instantaneous reception of optical images of moving subjects, images of which had been transmitted by means of a variable electric current, on January 27, 1926. Most of the scientific workers and publicists present at that demonstration, while impressed by the

achievement, were frankly sceptical of television ever achieving any position as a medium of entertainment or of its being put to other commercial uses. The received images were recognisable, but blurred and flickering, and to many scientific workers, a proof of the impossibility of advance in television by a mechanical system of transmission and reception. Other scientific observers, though less antipathetic to the mechanical system, were unconvinced that television broadcasting would ever be practicable owing to the wide range of frequencies which would have to be made available if images with detail comparing with that obtainable on a cinema screen were to be received. This was the more vital criticism of television, as it applied not only to the mechanical means by which Baird obtained his first results but also to any other means, for example, the utilisation of cathode rays, which might afterwards be enlisted in the service of television. 中文

Only minor modifications had been made of the original apparatus used when Baird gave his first demonstration to members of the British Association at Leeds in 1927. In 1926 the subject to be televised was bathed in light from a battery of powerful electric lamps. Between the photoelectric cells and the illuminated subject was a scanning device, a disc in which thirty holes were punched at regular intervals on a spiral and making five revolutions per second. The subject was thus scanned by a rotating optical element strip by strip, each strip being presented in sequence to a light sensitive element, the photoelectric cells. The varying strength of electric current transmitted by the photoelectric cells modified the light in a neon lamp at the receiving end, and this varying single light source was scanned in turn by a "Nipkow" disc synchronised with the disc at the transmitting end. The reconstituted image, two inches square, was seen by looking at the neon lamp through the scanning disc. Synchronism was obtained by the use of synchronous motors. 中文

For the Leeds demonstration “noctovision” was used, the person televised being shielded from the direct glare of the lamps by a sheet of ebonite. In the meantime, however, Baird had made a further notable advance by his invention of the light spot method of scanning. To quote the text of his patent: “The scene or object to be transmitted is traversed by a spot of light, a light sensitive cell being so placed that light reflected back from the spot of light traversing the object falls on the cell.” It is, in effect, an inversion of the flood-lighting method, and possesses the advantage that greatly increased signal strengths are obtained with considerable diminution in the intensity of the illumination to which the subject of transmission is exposed.

中文

Abroad, the method was almost immediately applied by the Bell Telephone Company in the United States in carrying out a television transmission over a circuit between New York and Washington. The same year, 1927, Belin and Holweck achieved a measure of success in transmitting outlines and shadowgraphs using a cathode ray oscillograph (Fig. 1). The success of Baird had given an impetus to research in television in several countries as the patent records of England, the United States, Germany and France will testify. 中文

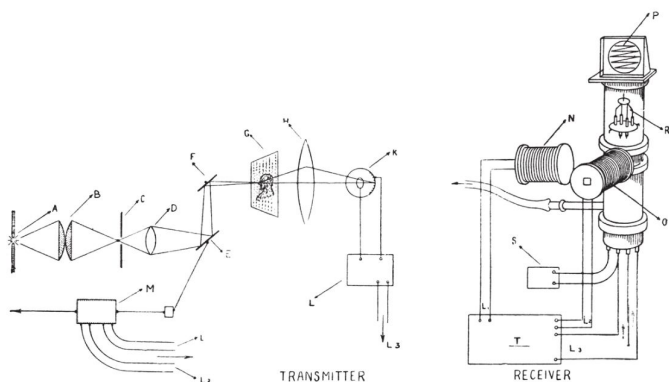


Fig. 1. Schematic diagram of Belin and Holweck's television apparatus.

中文

On February 9, 1928, Baird achieved an ambition to be the first to televise across the Atlantic. The signals were picked up in the presence

of Reuter's representative by an amateur operator at Hartsdale, a few miles from New York, the experimental receiver showing an image about three inches square on a ground glass screen. This Baird followed almost immediately by a transmission from London to the s. s. *Berengaria* in mid-ocean. According to the chief staff engineer of the vessel, the "image varied from time to time in clarity, but movements could be clearly seen, and the image, when clear, was unmistakable". In these transmissions the wave-length used was 45 metres. The following year, using light spot transmission and cathode glow lamp with disc reconstruction, Baird demonstrated in engineering form at the British Association meeting in Cape Town, and the British Broadcasting Corporation agreed to provide facilities for a series of experimental television broadcasts by the Baird system on the London B.B.C. transmitter. At this time, the transmission of wording for instantaneous news broadcasts, telegram transmission in character, languages and other purposes was further developed by Baird and transmissions of this kind were featured in the experimental broadcasts. [中文](#)

In July 1930, the Baird Company gave its first public demonstration in a theatre, living artists and cinema films being transmitted from its studios in Long Acre, London, W.C.2, and reproduced on a multi-cellular lamp screen on the stage of the London Coliseum. The same year the youthful Baron von Ardenne in Germany commenced his researches on television, utilising the technique acquired in his development of cathode ray oscillograph tubes for the transmission and reception of television images, and within a year earned the distinction of being the first to demonstrate publicly cathode ray reception comparable with that produced by mechanical means. At first, von Ardenne received images transmitted by mechanical means, but later, by using a variable velocity constant intensity cathode stream instead of one of varying intensity and constant velocity, he was able to employ his cathode ray tubes for transmission and

reception. 中文

Meanwhile, researches into the possibilities of cathode ray television were engaging the attention of a large number of scientific workers in the laboratories of the Radio Corporation of America and its associated enterprises, independently by the Philco and other American companies, and by the Fernseh A. G. of Berlin, in which the Baird Company are equal partners with Bosch, Zeiss-Ikon, and Loewe. The last-named holds important von Ardenne patent rights. In the Fernseh A. G. laboratories, research in cathode ray television was directed towards the development and utilisation of “hard” tubes, that is, tubes at pressures below 10^{-5} mm., as contrasted with the “soft” tubes in use by the Loewe Company, the advantage claimed for the hard tube being its long life, an important consideration. 中文

Proponents of mechanical methods, however, were by no means discouraged by the results obtained by the use of cathode ray tubes. The Baird Company, by using a mirror-drum instead of a Nipkow disc at the transmitting end, and at the receiving end using either a directly-modulated arc or a multiple Kerr cell in conjunction with a mirror-drum, was able to project fairly bright images on a screen about 6 ft. × 2 ft. in size, and demonstrated its results at the British Association centenary meeting in London, in the exhibition devoted to Mechanical Aids to Learning. This demonstration followed one in January 1931 in the Baird Laboratories at Long Acre of three-zone television, three 30-line mirror-drums being used to obtain an extended image. Later in the same month the Gramophone Company gave a similar performance in London at the Exhibition of the Physical and Optical Society, at which cinema films were transmitted by the multi-channel process and reproduced by means of a Kerr cell and mirror drum apparatus on a translucent screen. In the same year the Derby was televised by the Baird process. 中文

In 1932 five major events in the progress of television took place.

Fernseh A. G., the company organised to develop the Baird processes in Germany, built and installed a complete transmission equipment for the Ente Italiano per le Audizioni Radiofoniche in Rome; the Derby was televised and projected at the time of its occurrence upon the screen of a London cinema by the Baird Company; the British Broadcasting Corporation installed television transmission equipment designed by Baird Television Ltd., for regular transmissions from its London studio (Fig. 2); and the Baird Company designed and marketed a much improved home television receiver, the Nipkow disc and neon tube of the old type being replaced by a mirror-drum and Kerr cell combination for projecting the received image on a translucent screen: and Dr. Alexanderson, of the American General Electric Company, successfully transmitted and received television images over a light-beam, with apparatus and by methods similar to those demonstrated by the Marconi Company at Leicester at the recent meeting of the British Association. 中文

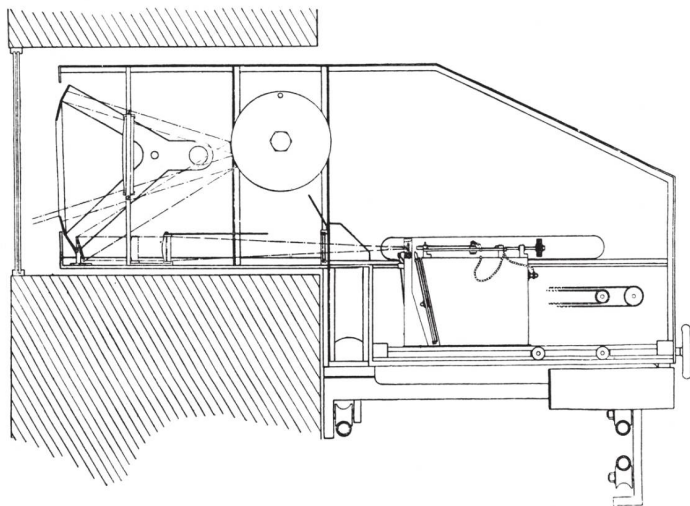


Fig. 2. A sectional scale drawing of the television transmitter as installed at Studio B. B., at Broadcasting House, London. 中文

This year has been one of feverish activity on the part of all companies interested in the commercial exploitation of television, and of numerous independent research workers in various countries. Many

interesting and ingenious modifications have been made in the cathode ray oscillographs. The Fernseh A. G. has made tubes with fluorescent ends with diameters up to 2 feet. Von Ardenne has devised a method of projecting the cathode ray beam from a plate within the tube on to an external screen. Von Mihaly has developed a mechanical system by which the modulated light of the receiver is swept by a small rotating mirror at the axis of a stationary drum across a number of mirrors fixed on its inside surface, for which he claims superiority over the revolving mirror-drum. The Fernseh A. G. laboratories have constructed beautifully accurate mirror-screws with 90 and 120 reflecting surfaces of stainless steel. Dr. Vladimir Zworykin, the American research engineer, has made sensational claims for what he terms his iconoscope, which has been described as consisting of two devices—a photoelectric mosaic on which a scene is focused by a lens system, and a cathode ray gun which fires at this mosaic screen a stream of electron projectiles. The signal plate on which the scene to be televised is focused may be about 4 in. $\times$ 5 in. in size and on this surface are millions of small photo-cells, each consisting of a minute silver globule sensitised by caesium. These globules are deposited on an insulating plate, such as a thin sheet of mica, the back of which is made conductive by a metal coating. Within the same glass bulb as the mosaic screen is the electron gun, which throws a beam of electrons at the screen and is made to sweep across the screen horizontally and vertically by deflecting coils as in an ordinary cathode ray tube. Whenever an electron hits a photocell, it neutralises part of the charge on the associated condenser. This discharge current is picked up, amplified and transmitted to the receiving cathode ray beam which is moving across a fluorescent screen in synchronism with the scanning beam. The varying discharge currents modulate this receiving beam and hence the screen at the receiver. It is reported that a similar device has been invented by Dr. Francis Henroteau, chief of the Dominion Observatory, Ottawa, who calls his invention the “super-eye”. If the claims can be backed up by practical

demonstrations, a new and important advance will be made in television. 中文

Again and again in the last two years, it has been urged that finer resolution than that obtainable with the 30-line standard, 2.4:1 ratio, picture is necessary before television will become popular. This may or may not be so, but the true nature of the present position should now be realised. In the first place, it is easily demonstrable (and it has in fact already been put forward) that, with a 10 kc./sec. band-width, the intelligence-time transmission characteristic of a channel (at a reasonable picture-speed such as 12.5 per second to minimise flicker) is most economically filled at about this number of lines and ratio.

中文

At the moment, pictures incomparably better than those possible with 30 lines, using mechanical reconstituting devices, are obtainable with cathode ray receiving apparatus which has become available this year. Such pictures were first demonstrated publicly in Great Britain by the Baird Company at this year's meeting at Leicester of the British Association and by Loewe, Fernseh A. G. and others at the Berlin Radio Exhibition, comprise 120–240 scanning strips, and require side band widths of from 150 kc./sec. to 1,000 kc./sec. for their proper transmission. In view of the Geneva convention, under which absolutely no provision was made for the proper expansion and development of television in the broadcast band of wave-lengths, an entirely new radio technique will have to be developed. Local areas, served by ultra short wave radio transmitters, seem an ideal solution. In practice, however, many difficulties arise, not the least of which is the shielding effect in populous areas of buildings, steel structures, trees, rises in ground contour, etc. Research in this direction is progressing; in fact, experimental short-wave transmissions of high quality pictures (that is, of 120-line definition or more) have already commenced in the London area, the Crystal Palace towers being

utilised for this purpose. But it may be a year or two before an established service throughout the country is achieved. In the meantime, further problems arise in connexion with distortion in amplifiers against which the weapons provided by Oliver Heaviside, to whose classic researches on the underlying electrical principles of distortion in communication engineering too little credit is given, are powerless. In extending the band-pass of an amplifier, the "temperature effect" dealt with by L. B. Turner in his inaugural address to the Institution of Electrical Engineers becomes an important factor in determining the interference level of a system; all the more so because an increase in the number of scanning strips in a picture involves the diminution, usually according to some power-function, of light available to affect the light sensitive cells. Further carefully directed research in this direction has become imperative for the transmission of actual scenes, as opposed to film broadcasts. For the projection of television pictures to large audiences in cinema theatres and elsewhere, Fernseh A. G. has recently demonstrated an "intermediate-film" method (Fig. 3). In this the televised image is received on a cinema film which is then developed and passed through an ordinary cinema projector, the time interval between the reception and projection being about 6 seconds if an ordinary reel of film is used, about 20 seconds if an endless loop of film is used, the "base" being first emulsified and dried, then exposed to the receiving scanning device, developed, projected and de-emulsified. This method shows great promise but much further work remains to be done on it.

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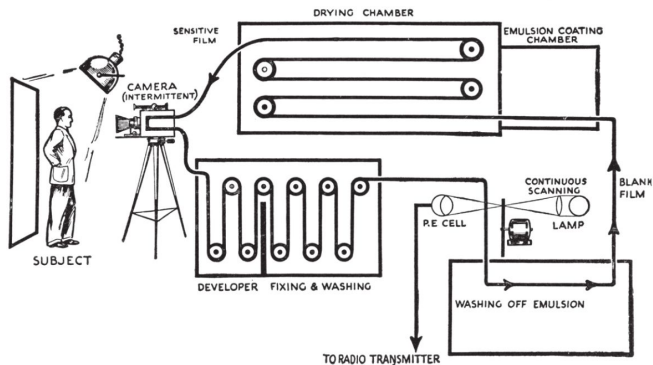


Fig. 3. Simplified diagram of the apparatus employed by Fernseh A. G. for the transmission of television by the intermediate film method. 中文

(132, 502-505; 1933)

* Paper read before Section A (Mathematical and Physical Sciences) of the British Association at Leicester on September 13.

电视技术的最新进展*

阿奇博尔德·丘奇

欧洲和美洲的公司在电视技术的研制方面正在展开竞争。正如阿奇博尔德·丘奇在这篇评论文章中所说的：当约翰·贝尔德在1926年首次向公众演示那些模糊和闪烁的电视图像时，人们普遍对此持怀疑态度，但现在这项技术正如火如荼地发展着。1932年，有人把德比马赛拍摄下来并实时传送给伦敦的观众；而且英国广播公司也已经安装了贝尔德电视有限公司的转播设备。现在工程师们正在想办法把阴极射线投射到荧光屏上以改善图像的质量，并使现场直播成为可能。这需要有较高的屏幕分辨率，而且还需要在广播频带中为电视信号安插一定的位置。 [英文](#)

电视技术的所有发展都是最近涌现出来的。从约翰·贝尔德第一次获得简单静态物体，例如马尔他十字形的电视图像到现在还不到10年时间。在1926年1月27日，贝尔德第一次演示了“真正”的电视，这个装置可以即时接收到运动物体的光学图像，图像的传输是通过电流的变化实现的。很多科学工作者和媒体人士都出席了这次演示会，虽然他们被这项成就深深震撼，但仍坦言对电视是否能成为娱乐业的媒介之一或是否能被应用于其他商业用途持怀疑态度。尽管人们可以分辨出接收到的图像，但比较模糊而且忽隐忽现，所以许多科学工作者认为，电视的发展不可能通过机械式的传送和接收系统来实现。尽管其他的科学观察者对机械系统的反对不那么强烈，但也不相信可以这样来实现电视的转播，因为电视图像要是能与电影院屏幕上播放的图像一样清晰，就需要有很宽的频率范围。这个提法对电视的发展更为致命，因为它不仅否定了贝尔德在获得初步成功时所应用的机械手段，也否定了将来有可能应用于电视技术的其他手段，如阴极射线。 [英文](#)

在贝尔德1927年首次在利兹向英国科学促进会成员展示电视的时候，这套设备仅仅做了很小的改动。在1926年时，人们用一组功率很高的电灯照射要被电视转播的物体。在光电管和被照射的物体之间有一个扫描设备，扫描设备是一个圆盘，在圆盘的周边沿螺线每隔一定间隔排列着30个小孔，圆盘每秒转5圈。一个旋转的光学元件一条一条地扫描要被电视转播的物体，每一条信息都会按顺序传递到一个光敏元件——光电管上。光电管中电流强度的变化会改变位于接收端的氖灯的亮度，且这个不断变化的单光源被一个与发送端扫描圆盘同步的“尼普科夫”盘（译者注：以德国发明家保罗·尼普科夫命名，尼普科夫发明螺盘旋转扫描器，用光电管把图像的序列光点转变为电脉冲，实现了最原始的电视传输和显示。）依次扫描。重新组合而成的图像面积为2平方英寸，我们可以通过扫描圆盘观察氖灯看到这个图像。同步的产生是由同步电机实现的。

[英文](#)

在利兹演示的时候，贝尔德使用了“红外线电视”，即为了避免被转播的人被灯光眩射，在人与灯之间隔了一层硬质橡胶。另一个显著的改进是贝尔德发明的光点扫描法。他在自己的专利中是这样写的：“用一束光扫过要传输的场景或物体，把光敏元件放置在这束照射到物体上又被反射回来的光能够经过的位置上。”这实际上是泛光照明法的一种倒置，它的优点是：可以大大增加所得信号的强度，因而可以适当减少照射到被电视转播的物体上的光亮度。

[英文](#)

在国外，美国的贝尔电话公司很快就开始应用这种方法通过一个电路在纽约和华盛顿之间实现了电视传输。同一年，也就是1927年，贝林和霍尔威克使用阴极射线示波器（图1）成功地传送了轮廓线和影像图。在贝氏成功的激励下，好几个国家都开始开展电视方面的研究，英、美、德、法的大量专利记录可以证明这一点。

[英文](#)

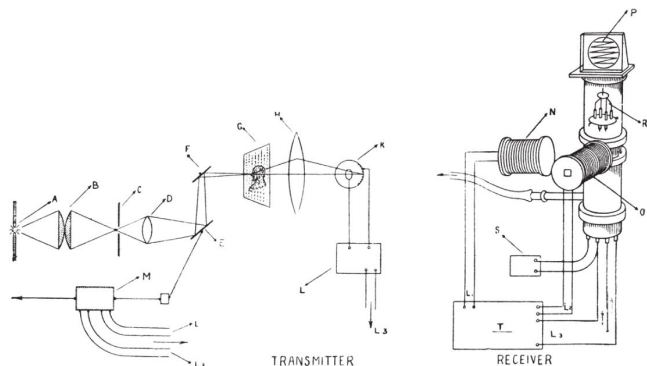


图1．贝林和霍尔威克所用电视设备的示意图 [英文](#)

1928年2月9日，贝尔德第一个实现了在大西洋两岸传送电视信号的目标。在距离纽约几英里远的哈茨戴尔镇，一个业余操作员当着路透社代理人的面接收了电视信号，他用实验接收设备在一个毛玻璃屏上显示出了大小约3平方英寸的图像。贝尔德很快又将伦敦的电视信号传送到航行在大洋中央的伯伦加利亚号船上。该船的首席工程师说：“图像的清晰度不太稳定，但可以很清楚地看到运动变化，图片在清晰的时候是准确无误的。”转播使用的波长为45米。第二年，使用光点传输法和带有可实现图像重建的圆盘的阴极辉光灯，贝尔德在英国科学促进会于开普敦召开的会议上按照工程学的模式进行了演示，英国广播公司（BBC）同意为在伦敦BBC的发射机上使用贝氏系统进行一系列的实验性电视转播提供设备。同时，贝尔德还研制出实时播送新闻广播节目的语音以及用电报传输字符、语言和其他内容的方式，类似这样的传输构成了实验性转播中的主要特征。 [英文](#)

1930年7月，贝尔德公司在一家剧院进行了首场公开演示，艺术家的现场表演和电影胶片从位于伦敦W.C.2区朗埃克的演播室中被传送出去，并重现在伦敦剧院舞台上的一个多管灯屏幕上。同一年，年轻的冯阿登爵士在德国开始了他对电视的研究，他采用自己研制的、专用于传送和接收电视图像的阴极射线示波管，在不到一年的时间里，他就因第一个向公众展示能与机械式接收系统性能相媲美的阴极射线接收器而声名卓著。起初，冯阿登接收的是通过机械手段传送的图像，但是后来他利用一个速度可变、强度不变的阴极电子流来代替速度不变、强度变化的电流，这样就使他的阴极射线管既能传送图像又能接收图像了。

与此同时，对阴极射线电视的研究吸引了许多在美国无线电公司及其联营企业，主要是飞歌公司和其他美国公司，以及在德国柏林电视机股份公司工作的科学工作者们的注意，在柏林电视机股份公司中，贝尔德公司与博世公司、蔡司伊康公司以及洛伊公司的股权地位相当。洛伊公司是冯阿登专利的主要拥有者。柏林电视机股份公司的实验室在研制阴极射线电视时采用的是“硬”管，即压力低于 10^{-5} mm的管子，与之相反洛伊公司使用的是“软”管，“硬”管所具有的优势是寿命长，而寿命是人们主要考虑的因素。

英文

然而，机械方法的支持者丝毫没有因阴极射线管所取得的成功而感到沮丧。贝尔德公司在发送端用镜面鼓代替尼普科夫圆盘，在接收端或者用一个直接被调制的弧光灯或者用克尔盒与一个镜面鼓联用，这样就能把很亮的图像投射到一个大小约6英尺×2英尺的屏幕上，并且贝尔德公司在英国科学促进会于伦敦召开的成立百周年纪念大会上的以“机械手段辅助学习”为主题的展览中演示了他们的成果。1931年1月，在贝尔德位于朗埃克的三段式电视实验室中，他们又演示了一次他们的成果，用3个30线的镜面鼓得到了持续时间较长的图像。在同一月的稍晚些时候，留声机有限公司在物理和光学学会于伦敦举办的展览上进行了类似的演示，他们用多通道方式传送电影胶片上的信息，并通过克尔盒和镜面鼓把重新生成的图像投射到一个半透明的屏幕上。同一年，贝氏方法被用于转播德比马赛。

英文

1932年发生了5件对电视业发展影响重大的事情。德国人为了应用贝尔德的技术组建了柏林电视机股份公司，公司为广播电台设于罗马的意大利办事处安装了一整套电视转播设备；贝尔德公司通过电视转播把德比马赛的现场实时地传送到了伦敦电影院的大屏幕上；英国广播公司也安装了由贝尔德电视有限公司设计的电视转播设备，以用于其伦敦演播室的定期转播（图2）；贝尔德公司还设计了一种更先进的家用电视接收设备并投放到市场中，在这种新设备中，原来用于把接收图像投射到半透明屏幕上的尼普科夫圆盘和老式氛管被镜面鼓和克尔盒的组合体所取代；美国通用电气公司的亚历山德森博士成功地利用光束发送和接收到了电视图像，他所用的设备和方法与马可尼公司在英国科学促进会

最近于莱斯特召开的会议上所作的演示类似。

英文

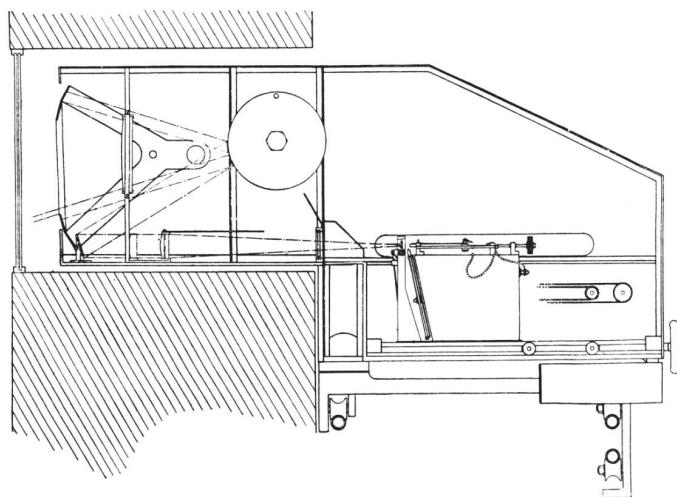


图2. 安装在英国广播公司伦敦广播大楼内演播室中的电视发射机的截面图

英文

今年，所有对电视商业开发感兴趣的公司和来自不同国家的大批独立研究者都表现出了很高的研究热情。大家对阴极射线示波器进行了大量有趣和富有创造力的改进。柏林电视机股份公司制造出了末端发荧光的管子，其直径可达2英尺。冯阿登设计了一种可以把从管内一个板上发射出来的阴极射线束投射到外部屏幕上的方法。冯米哈伊开发了一套机械系统，在该系统中接收器中的调制光被一个旋转的小镜子扫过，小镜子位于一个静止圆筒的轴线上，正对着固定在圆筒内表面上的许多镜子，他宣称这套系统优于旋转的镜面鼓。柏林电视机股份公司的实验室还造出了非常精确的镜面螺旋，在螺旋轴上装有90和120个不锈钢的反射面。美国研发工程师维拉蒂米尔·斯福罗金惊人地宣布他设计出一种他所谓的光电摄像管，该管由两部分组成，一个是透镜系统把场景聚焦在其上的嵌镶光电阴极；另一个是向嵌镶光电阴极发射电子束的阴极射线枪。要转播的场景被聚焦到大小约4英寸×5英寸的信号板上，信号板表面有数以百万计的小光电管，每个光电管都包含一个被铯敏化的，易于感光的小银球。这些小球被置于一块绝缘板上，譬如薄的云母片上，在其背面涂有一层金属因而可以导电。电子枪与嵌镶光电阴极被放在同一个玻璃泡内，在与普通阴极射线管相同的偏转线圈的作用下，电子枪发射的电子束水平和垂直地扫过嵌镶光电阴极。一旦一个电子打在了光电管上，它就会中和对应聚光器上的部分电荷。这种放电电流被采集、放

大并发送到接收端的阴极射线束上，这些阴极射线束随着扫描束同时移动到另一侧的荧光屏上。不断变化的放电电流使接收端的阴极射线束被调制，因而也调制了接收端的屏幕。据报道，渥太华自治领天文台的台长弗朗西斯·亨罗托博士也发明了一种类似的设备，他把自己的发明称作“超级眼”。如果这些设计都能付诸实践，那么在电视领域就将出现具有重大意义的革新。 [英文](#)

人们在过去的两年中一直认为：为了使电视得到普及，就必须研制出图像清晰度高于已有的30线标准、画面比例为2.4:1的电视。事实可能是这样，也可能不是这样，但我们应该清楚现在的真实情况。首先，很容易证明（实际上已经有人提出过）当带宽为10千赫时，一个频道的信息-时间传输特性（为了使闪烁最小化，应达到一个合理的图像速率，如每秒12.5次）采取这样的线数和比率最为经济。 [英文](#)

目前，利用今年研制出的阴极射线接收设备所得到的图像的质量明显优于机械式接收设备重组而成的30线图像。贝尔德公司在英国科学促进会今年在莱斯特召开的会议上首次公开展示了这种质量的图像，洛伊公司、柏林电视机股份公司等其他公司在柏林无线电展览上也展示了同样的产品，包含120~240个扫描带，正常传输所需的边带带宽为150千赫到1,000千赫。因为日内瓦公约中没有任何一个条款在广播波段中为电视业的合理扩张和发展预留出一定的波长区，所以人们不得不想办法开发全新的无线电技术。在局部地区使用超短波无线电发射机似乎是一个理想的解决办法。然而，在实践中应用这种方法时遇到了很多困难，其中之一是许多地方因建筑物、钢结构、树木和地平面以上的高地等导致了屏蔽效应。目前人们正在进行这方面的研究；实际上在伦敦，人们已经开始试验用短波传输高质量的图像（即清晰度达到120线或更高的图像），为此目的用上了水晶宫的双塔。但要在全国范围内建立这样的服务恐怕还需要一两年。与此同时又出现了许多与放大器失真有关的问题，虽然奥利弗·赫维赛德对通信工程中的基础电学失真原理进行了可靠的研究，但他的研究成果在实践中的可信度太低，因而对解决这个问题无能为力。如果扩大一个放大器的带通，那么特纳在电气工程师学会的就职演说中提到的“温度效应”就会成为决定系统受干扰程度的一个重要因素；更因为在了一幅图中扫描带数量的增加会使照射到光敏元件上的光

以幂函数的形式迅速下降。与胶片播放不同，我们需要对实际场景的转播定向进行更加细致的研究。为了给电影院或其他场所的广大观众放映电视图像，柏林电视机股份公司最近展示了“中间胶片”的使用方法（图3）。在这个过程中，电视图像被传送到一个电影胶片上，然后被冲洗并通过一个普通的电影放映机播放出来，如果使用的是普通胶卷，则接收和放映过程大约需要6秒，如果使用循环胶卷，则所需的时间约为20秒，“片基”首先被乳化和干燥，接着进入接收端的扫描设备，然后冲洗、放映和去乳化。尽管这种方法具有广阔的前景，但仍有很多更进一步的工作需要做。 英文

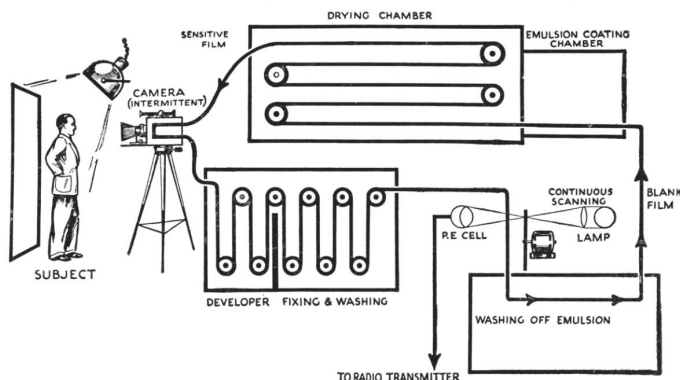


图3．柏林电视机股份公司利用中间胶片法传送电视节目所用装置的示意图 英文

（刘霞 翻译；赵见高 审稿）

* 这篇论文曾在英国科学促进会A分会（数学和物理学分会）于9月13日在莱斯特举行的会议上被宣读过。

Production of High Magnetic Fields at Low Temperatures

K. Mendelssohn

Kurt Mendelssohn here reports an important experimental advance in the generation of powerful magnetic fields at low temperatures. Using superconducting alloys able to bear field strengths up to 22,000 gauss at a temperature of just 2 K, he and colleagues had experimented with a transformer-like arrangement of magnetically coupled coils. A magnetic field of 1,000 gauss created in a conducting primary coil was made to induce current in a secondary superconducting coil. With a dense coil solenoid as part of the second coil, the device could produce a field of 22,000 gauss in a small volume. This achievement, Mendelssohn points out, might be used to create extremely low temperatures by the method of adiabatic demagnetization. [中文](#)

THE use of a supra-conductor (therefore completely free from Joule heating) has been more than once suggested for the production of magnetic fields at low temperatures. The magnetic field obtainable by this means is limited by the magnetic threshold value at which supra-conductivity ceases. Still, considerable fields can be obtained by the use of alloys (investigated in Leiden¹) the threshold value of which is 22,000 gauss at 2° K., a strength which is sufficient for many experiments. [中文](#)

The chief remaining difficulty lies in the heat conductivity of the leads to the supra-conducting coil. This problem of heat conduction through the leads can be eliminated by transferring the necessary energy for the magnetic field by induction. The suggested arrangement is similar in principle to a transformer, the primary circuit of which is normally conducting and the secondary circuit of which is supra-conducting. The primary circuit consists of a D. C. source and the primary of the transformer; the supra-conducting secondary circuit consists of a secondary with a few turns of large radius and a solenoid with many narrow turns for producing the high field. On closing the primary circuit the magnetic energy transferred to the secondary is shared with the solenoid. With this arrangement, one produces, to some extent, condensation of the lines of force. Calculation shows that for given geometrical dimensions there is an optimum ratio for the number of turns in the secondary coil to that in the solenoid. In this way, within the limits of the usual dimensions of an apparatus, it is easily possible with a primary field of about 1,000 gauss to obtain a field of 22,000 gauss in the space of a few cubic centimetres. 中文

The method should be specially suitable whenever it is desired to produce fairly high magnetic fields at low temperatures in not too large a volume, as, for example, in the production of extremely low temperatures by the adiabatic demagnetisation of paramagnetic substances². According to the experiments of Kürti and Simon³, Giauque and MacDougall⁴ and de Haas and his co-workers⁵, it should be possible, with the above arrangement, to obtain temperatures below 0.1° K. from a starting point of 1° K. Since heat conductivity along the current leads is eliminated, and since heat capacities at helium temperatures are so minute, a few cubic centimetres of liquid helium should suffice to cool the whole arrangement. 中文

Experiments with an apparatus embodying the above methods are

being made in this laboratory. 中文

(132, 602; 1933)

K. Mendelssohn: Clarendon Laboratory, Oxford. Sept. 28.

References:

1. de Haas, W. J., and Voogd, J., *Comm. Leiden*, No. 214b (1931).
2. Debye, P., *Ann. Phys.* (4) **81**, 1154 (1926); Giaque, W. F., *J. Amer. Chem. Soc.*, **49**, 1864 (1927).
3. Kürti, N., and Simon, F., *Naturwiss.*, **21**, 178 (1933).
4. Giaque, W. F., and MacDougall, D. P., *Phys. Rev.*, **44**, 235 (1933).
5. de Haas, W. J., *Nature*, **132**, 372 (Sept. 9, 1933).

低温下强磁场的产生

库尔特·门德尔松

在这篇文章中，库尔特·门德尔松报告了自己在制造低温强磁场的实验技术上取得的重大突破。在温度仅为2 K的情况下，利用可以承受高达22,000高斯强磁场的超导合金，他和同事们用一种类似于变压器的线圈排布方式的磁耦合线圈进行实验。他们首先在导电的初级线圈上施加1,000高斯的磁场以便在次级超导线圈上产生感应电流。次级线圈的一部分是缠得很密的螺线管，这台装置可以在一较小的空间内产生22,000高斯的磁场。门德尔松指出：这项技术的成功也许可以用于通过绝热退磁法产生极低温。 [英文](#)

已经不止一次有人提出可以利用超导体（完全没有焦耳热）在低温下产生磁场。但用这种方式获得的磁场要受到超导电性消失所对应的磁场阈值的限制。尽管如此，利用温度为2 K时阈值可达22,000高斯的合金（在莱顿的研究结果^[1]）仍可以产生强度可观的磁场，这个强度对许多实验来说是足够了。 [英文](#)

剩下的主要困难在于超导体线圈的引线存在热传导。我们可以通过磁场感应传递必要的能量来消除导线中的热传导问题。已提出的实验装置在原理上与变压器相类似，其主回路是正常传导的回路，而次级回路是超导回路。主回路包括直流源和变压器的初级回路；而次级超导回路则包含一个由几匝粗线圈绕成的次级回路和一个用来产生强磁场的由许多匝线圈密绕成的螺线管。当主回路接通时，传递到次级回路的磁能中的一部分分到螺线管上了。我们利用这台装置在一定程度上使磁力线变密了。计算表明，对于给定的几何尺寸，存在次级线圈匝数与螺线管匝数的一个最佳比值。这样，在通常的装置尺寸的极限内，我们很容易由1,000高斯的初级场在几个立方厘米的空间内获得高达22,000高斯的磁

场。 英文

这个方法应该特别适用于要求在低温下的一块不太大的体积内产生超强磁场的情况，例如利用顺磁物质的绝热退磁产生极低温的情况^[2]。根据库尔蒂和西蒙^[3]、吉奥克和麦克杜格尔^[4]以及德哈斯及其同事们^[5]的实验，用上述装置从1 K的初始温度得到0.1 K以下的温度应该是可以办到的。由于消除了沿着电流导线的热传导，而且在液氦温区热容量也很小，所以几立方厘米的液氦就足以冷却整台装置了。 英文

我们正在实验室中利用根据上述方法设计的仪器进行实验。 英文

（沈乃澂 翻译；赵见高 审稿）

New Results in Cosmic Ray Measurements*

E. Regener

Erich Regener reports in more detail on his observations of the ionisation caused by cosmic rays in the upper atmosphere. Using electrometers born aloft in balloons, he and colleagues made a number of measurements at very high altitudes, where the air pressure fell below 50 mm Hg. In three trials, their devices gave consistent results; a fourth did not, but Regener noted that other researchers had observed a magnetic storm on this day which may have disturbed the measurements. In total, the data suggested that the cosmic radiation consisted of three distinct components of different penetrating power. [中文](#)

IN recent years I have endeavoured to explore the decay of the intensity of cosmic radiation over as wide a range as possible after its entrance into the earth's atmosphere. I believe that such an investigation is indispensable before a theory of the nature of cosmic radiation can be put forward. In *Nature*¹ and in the *Physikalische Zeitschrift*² I have already given some preliminary account of our measurements of the intensity of the cosmic radiation in the upper atmosphere. I propose to give here some further results, obtained in recent ascents with registering balloons, but first a few improvements of the apparatus which we have introduced must be described. [中](#)

[文](#)

The balloon electrometer includes an electrometer system (a thin Wollaston wire, a quartz sling giving the directing power), the photographic objective, projecting the electrometer wire on the photographic plate. The wire is illuminated every four minutes from the side, so that it appears bright on a dark background on the photographic plate. There is also an aneroid barometer for the measurement of the air pressure and a bimetallic lamella for measuring the temperature. The movement of the aneroid, when the pressure decreases, limits by a pointer the image of the electrometer wire on the photographic plate. Since the measurement of the pressure is the most delicate part, especially when the pressure is low, we have added to the ordinary aneroid a second one, which only starts indicating when the pressure falls below one hundred millimetres. By observing the balloons in the air with two theodolites from a base of three to four kilometres, we have been able to prove that the measurements of the pressure with these two aneroids are fairly exact. The agreement with the height deduced from the pressure measurements was very good. [中文](#)

We have also employed another form of balloon electrometer. Our balloon electrometers hitherto constructed each had the ionisation chamber filled with air at a pressure of three or four to five atmospheres. The new electrometer has an *open* ionisation chamber, that is to say, a chamber communicating with the air outside through a tube containing phosphorus pentoxide. The pressure in this chamber decreases as the balloon rises in the free atmosphere, and the ionisation chamber in this case must be larger in order to obtain adequate sensitivity. But such an arrangement is very convenient for measuring the absolute value of the ionisation due to the radiation, because it is much easier to obtain the saturation current at a low pressure. In the ordinary ionisation chamber, which is filled with gas at high pressure, it is well known that it is very difficult to obtain the saturation current. [中文](#)

Fig. 1 shows the results of the four best registrations of the cosmic radiation with the closed balloon electrometer. The minimum values of the air pressure on these four ascents are respectively:

August 12, 1932: 22 mm. mercury, 5.4 atmospheres pressure in the ionisation chamber.

January 3, 1933: 34 mm. mercury, 4.45 atmospheres.

March 9, 1933: 17.6 mm. mercury (this is the lowest pressure hitherto reached), 3.28 atmospheres.

March 29, 1933: 32 mm. mercury, 5.33 atmospheres. 中文

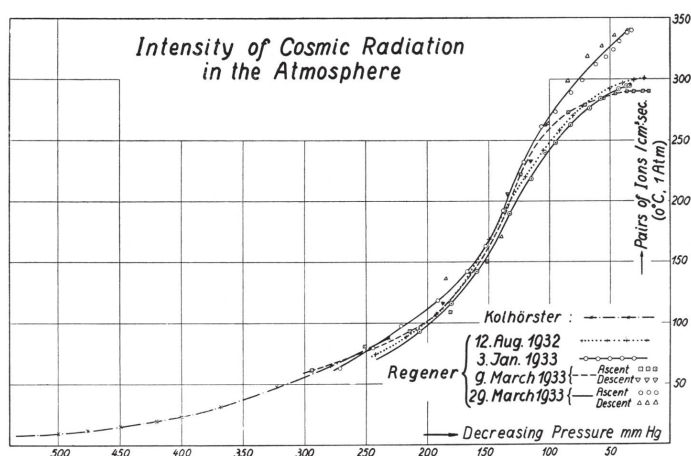


Fig. 1. 中文

It is noteworthy that the first three ascents agree very well among themselves. Also the fourth ascent agrees with the others very well at the medium heights at a pressure of 150 mm. mercury (that is, at a height of about twelve kilometres). But in the upper atmosphere, that is, at pressures of less than 100 mm., at heights greater than fifteen kilometres, and even more so at heights of twenty kilometres, the intensity begins to be much greater than on the other ascents, so that the maximum value is nearly fifteen percent greater than on the other ascents. This is probably *not* due to the inaccuracy of the

measurements. It can be seen that the middle parts of the fourth curve agree very well with the others. Moreover the fourth registration, of March 29, 1933, is the best of all with the closed electrometers. It was also possible to obtain observations during the descent of the balloon (Fig. 1). These observations showed that the ordinary and the secondary aneroids worked very well. 中文

The temperature during the hour in which the balloon was in the stratosphere varies comparatively little, from 6.5° to 11° °C. That is due to the “Cellophane” case, surrounding the electrometer like the glass of a forcing house and protecting it against the cold in the stratosphere. 中文

We believe that the difference of the fourth curve from the others is real, and we have tried to find an explanation. We searched for the cause in the circumstances accompanying the four ascents. On the fourth ascent there was a new moon and we thought that perhaps radioactivity of the moon was the cause of the greater intensity on this day; for on the other ascents the moon was not in the sky. Incidentally, it should be noted that at a pressure of twenty or thirty millimetres of mercury, already one-third of the γ -radiation of ordinary radioactive bodies could penetrate into the atmosphere. But a little calculation shows that the radioactivity of the moon would have to be improbably great to do this, so this explanation cannot be true. Then we inquired into the magnetic disturbances on the four days. Both Prof. A. Nippoldt at Potsdam and Dr. A. Corlin in northern Sweden informed me that on March 29 there was a magnetic disturbance of medium strength, but the other days were magnetically calm. It would be remarkable if there were a connexion between the magnetic intensity and the intensity of the cosmic rays in the highest parts of the atmosphere, and only in the highest parts; that is to say, that there are additional rays (soft rays) there, perhaps coming from a sunspot. But up to now we have observed this but once. Further

observations are necessary in order to ascertain whether this is real.

中文

From the measurements of the decay of the intensity of the cosmic radiation in Lake Constance, my collaborator, Dr. W. Kramer³, has deduced that there are many components of the radiation. 中文

From Sir James Jeans's hypothesis, one can calculate that the hardest two components correspond to the annihilation of a helium atom and of a proton. But there are many assumptions in this calculation. It is often objected that the fact ascertained in our ionisation curve in the atmosphere, that the ionisation curve approaches a maximum value at the top of the atmosphere, is *not* in favour of the hypothesis, that the primary radiation is electromagnetic. Electromagnetic radiation coming from outside into the atmosphere of the earth will produce secondary radiation, and we shall find a maximum value of the intensity in the lower atmosphere, perhaps at twenty kilometres, and the intensity will diminish towards the top of the atmosphere. 中

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It is easy to show, however, that the observed form of the ionisation curve agrees with the assumption that the radiation is electromagnetic. The observed curve is altered by the fact that the rays come from all directions. The rays coming from the side, that is, the rays which are already saturated with secondary radiation, because of the long distance they have travelled, are of greater account. My collaborator, Mr. B. Gross⁴, has shown that it is possible to calculate from the curve observed for rays incident in all directions the corresponding curve of uni-directional rays. If the function for the rays from all directions be I_x , and ψ_x be the corresponding function for the intensity of rays coming from one direction only, then

$\psi_x = I_x - I_x \frac{dI_x}{dx}$. The curve for rays entering the atmosphere vertically shows that their intensity diminishes towards the top of the atmosphere. Thus it agrees with the suggestion that at least a part of

the radiation is electromagnetic. There is also a second maximum produced by the second component of the soft part of the radiation.

中文

I would like to add a few words about the analysis of the radiation into its components. My collaborator, Dr. E. Lenz⁵, has worked out a useful method for finding whether the radiation is monochromatic or contains more than one component. This method is independent of any assumption regarding the nature of the rays. Suppose that the intensity is a monotonic function of the absorption of monochromatic radiation. When the intensity I is multiplied by the thickness d of the absorbing layer, this gives a curve with a maximum at a certain value of d . If the radiation consists of two components of different penetrating power, then there are two maxima in the curve (let us say in the *deformed* curve), deduced from the original curve by multiplying the intensity by the thickness of the layer. When our experimental results are plotted in this way, the curve shows that the radiation in the atmosphere consists of two or three components of different penetrating power. 中文

It is also possible in an experimental way to decide whether the decomposition of the radiation in components is real. When the intensity of radiation in the free atmosphere is observed with an open ionisation chamber, we do the same as we have just done in a mathematical way. The ordinary curve of the intensity of the radiation is a curve obtained with an ionisation chamber containing air at a pressure of one atmosphere. When we work with an open ionisation chamber, we find a value of the current in the chamber which is smaller in the same ratio as the pressure in the air, and thus in the chamber also, is smaller than the normal pressure. Thus we obtain directly a deformed ionisation curve, because the pressure is in proportion to the mass of the layer which is penetrated by the rays.

中文

The two measurements made with such an ionisation chamber do not quite satisfy us yet. The first chamber employed was too small (volume only 22 litres) and therefore the sensitivity was inadequate. The second chamber had a volume of 105 litres and therefore the sensitivity was sufficient. A photographic record obtained on August 30 gave good results, but unfortunately the temperature of the instrument went down very low, below -20°C ., and therefore the corrections needed were a little greater than usual. The apparatus had become too heavy (3.7 kgm.) for our balloons and we did not employ sufficient safeguards against the cold. But on working out the registrations, the curve (Fig. 2) is already better than those with the closed chamber, and agrees very well with the deformed curve calculated above. The second maximum is also noticeable as in the deformed curve, but this maximum is not very distinct and we shall try to ensure more favourable conditions so that as few corrections as possible are necessary. This part of the curve, I believe, is most important for the analysis and the explanation of the curve. 中文

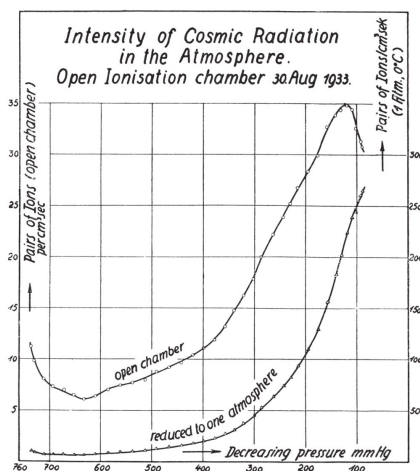


Fig. 2. 中文

In general, the method of employing the open ionisation chamber is very convenient if one wishes to obtain the whole curve from sea-level to the top of the atmosphere, because the observed values with the open chamber vary only from 1 to 5, while the ionisation in the closed

chamber varies from 1 to 150. Thus, in Fig. 2, the normal intensity curve is more accurate in the lower parts than with the closed chamber. The values for the normal curve are obtained from the values with the open chamber by multiplying them by p_0/p . 中文

I offer my thanks to Mr. B. Auer for helping me in the measurements and to the Notgemeinschaft der Deutschen Wissenschaft for supporting my investigations. 中文

(132, 696-698; 1933)

E. Regener: Technical High School, Stuttgart.

References:

1. Regener, E., *Nature*, **130**, 364 (1932).
2. Regener, E., *Phys. Z.*, **34**, 306 (1933).
3. Kramer, W., *Z. Phys.*, **85**, 411 (1933).
4. Gross, B., *Z. Phys.*, **83**, 214 (1933).
5. Lenz, E., *Z. Phys.*, **83**, 194 (1933).

* Paper before Section A (Mathematical and Physical Sciences) of the British Association, delivered at Leicester on September 8.

宇宙射线测量中的新结果*

埃里克·雷格纳

埃里克·雷格纳详细地报告了他在研究高层大气中宇宙射线的电离作用时得到的观察结果。他和他的同事利用气球载静电计在气压低于50毫米汞柱的高海拔区做了多次实验。他们的装置在前三次实验中给出了一致的结果；但第四次的实验结果与前三次有偏离，不过雷格纳指出其他研究人员在第四次实验的那天观测到了磁暴，这也许是导致实验结果出现偏离的原因。所有这些数据都说明了宇宙辐射是由三种穿透力明显不同的成分组成的。 [英文](#)

在最近几年里，我一直致力于探索宇宙辐射进入地球大气层后在尽可能广的范围内的强度衰减。我确信这项研究在我们提出一个有关宇宙辐射性质的理论之前是必不可少的。我已经在《自然》^[1]杂志和《物理杂志》^[2]上对我们测量高层大气中宇宙辐射强度的方法作了初步的说明。在这里我想给出一些更进一步的结论，是我们最近用探空气球的上升实验得到的，但首先我必须描述一下我们对这些仪器所做的改进。

[英文](#)

探空气球静电计包括一个静电计系统（一根细的沃拉斯顿铂丝，一个提供下坠动力的石英吊坠）和一个将静电计的铂丝投影到摄影底片上的照相物镜。来自边缘的光每隔4分钟把铂丝照亮一次，所以铂丝在摄影底片的暗背景中出现一条亮线。还有一个用于测量气压的无液气压计和一个用于测量温度的双金属片。当压力下降时，无液气压计的运动通过一个指针来限制静电计的铂丝在摄影底片上的图像。因为气压测量是最精细的部分，尤其是当压力很低时，因此除这个普通的无液气压计外我们又添加了第二个无液气压计，新添的气压计只有在气压低于100毫米汞柱时才开始有显示。通过在3~4千米高的基地上用2个经纬仪观察

空中的气球，我们已经能够验证用这两个气球上的无液气压计测量出来的压力是非常精确的，从压力测量中推导出来的高度与实际高度非常吻合。 英文

我们也使用过另一种形式的气球静电计。至今为止，我们使用的每一只气球静电计都配有电离室，室内充有3或4到5个大气压的空气。而新的静电计有一个开放的电离室，也就是说，电离室是通过一根装有五氧化二磷的管子同外部大气相通的。因此，当气球在自由大气中上升时，电离室内的气压也会随着下降，而且此时的电离室必须做得更大一些，以获得足够的灵敏度。开放电离室的设计非常便于测量由辐射产生的电离的绝对值，因为在低压下更容易达到电流的饱和。大家都知道在充有高压气体的普通电离室中，电流很难达到饱和。 英文

图1中显示的是我们用密闭气球静电计测量宇宙辐射的四次最佳实验结果。在这四次升空过程中达到的气压的最小值分别为：

1932年8月12日，22毫米汞柱，电离室内为5.4个大气压。

1933年1月3日，34毫米汞柱，室内4.45个大气压。

1933年3月9日，17.6毫米汞柱（这是迄今为止达到的最低气压值），室内3.28个大气压。

1933年3月29日，32毫米汞柱，5.33个大气压。 英文

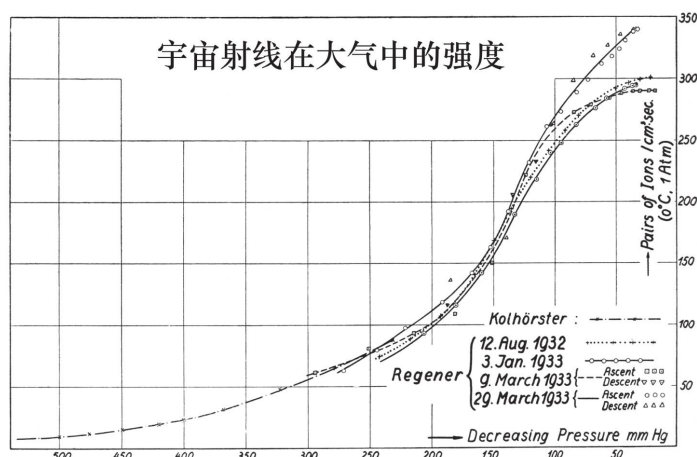


图1 英文

值得注意的是，前3次升空的结果相互之间很一致，第4次升空在气压为150毫米汞柱左右的中高度区（即在高度约为12千米时）所得的结果与前3次也很一致。但是到了上层大气中，即在气压低于100毫米汞柱，高度大于15千米甚至达到20千米时，其强度开始超过其他三次实验，最大值比其他几次实验高出近15%。这很可能不是由测量的不准确造成的。我们可以看到，第四个曲线的中部同其他曲线的中部非常吻合。而且，在1933年3月29日进行的第四次实验中我们采用了密闭的气压计，效果应该是最好的。在气球下降过程中，我们也可以记录观测数据（见图1）。这些观测结果表明，普通无液气压计和第二个无液气压计的工作状态都非常好。 [英文](#)

当气球在平流层飞行时，温度变化相对比较小——从6.5℃到11℃。那是因为“玻璃房”效应，静电计的周围被像温室的玻璃一样包裹着，使它能够抵御平流层的寒冷。 [英文](#)

我们相信，第四次实验得到的曲线与前三次结果之间的差别是真实的，而且我们曾试过做出解释。我们在四次实验所处的环境中寻找原因。在第四次实验时，出现了一轮新月，我们认为，月面的放射性或许是造成那天强度更大的原因，因为在其他几次实验中，天上没有出现月亮。顺便说一下，我们应该知道，当气压低到20或30毫米汞柱时，一般的放射性物体发射的 γ 射线就已经有三分之一能够透过大气了。但在经过了简单的计算之后，我们发现月亮的辐射不可能造成这么大的影响，所以这个解释是不正确的。接着，我们又查询了这四天内磁场扰动的情況。德国波茨坦的尼波德教授和瑞典北部的科林博士告诉我，在3月29日出现过一次中等强度的磁扰，而在另外三天内没有发生磁扰。如果在大气层顶部的磁场强度和宇宙射线强度之间存在着关联，而且这种关联只发生在大气层顶部，这一现象是非常值得关注的；这意味着，那里还有其他射线（软射线）存在，它们也许来自于太阳黑子。但是因为这样的现象我们至今只观察到过一次，要证实这种关联是否存在有必要进行进一步的观测。 [英文](#)

根据在康斯坦次湖进行的宇宙辐射强度衰变的测量结果，我的同事克雷默^[3]博士曾经作出推断，即宇宙辐射是由多种成分组成的。 [英文](#)

根据詹姆斯·金斯爵士的假设，我们能够计算出宇宙射线中最硬的两种成分与氢原子和质子的湮灭有关，但在计算过程中用到了许多假设。我们在整个大气层中得到的电离曲线证明，电离曲线在大气层顶部时会达到最大值；对于这一事实不支持初级宇宙射线为电磁辐射的假设，常常遭到众人的置疑。来自外太空的电磁辐射在进入地球大气层后会产生次级辐射，我们会在较低的大气层中，比如20千米处，发现射线强度达到最大值，而后在逐渐接近大气层顶部的过程中强度会有所下降。

英文

然而，我们很容易证明，通过实验得到的电离曲线与宇宙射线是电磁辐射的假设并不矛盾。射线来自于各个方向的事实改变了观测到的曲线。来自于侧面的射线，也就是那些在穿越了很长距离之后次级辐射已经达到饱和的射线，是非常重要的。我的同事格罗斯^[4]先生曾经指出，根据观察到的来自各个方向的辐射曲线可以计算出与单一方向对应的辐射曲线。假设来自各个方向的射线的函数是 I_x ，只来自于一个方向的射

线强度函数是 ψ_x ，则 $\psi_x = I_x - I_x \frac{dI_x}{dx}$ 。我们从垂直射入大气层的辐射曲线中可以看到，它们的强度在到达大气层顶部时会下降。因此，这与至少有一部分射线是电磁辐射的观点相符。射线中软射线部分的次级成分还会产生第二个极大值。

英文

对于分析射线的各种成分，我还想再多说几句。我的同事伦兹博士^[5]已经找到了一种区分射线到底是单组分还是多组分的方法，该方法独立于任何有关宇宙射线性质的假说。假定强度是对单色辐射进行吸收的单调函数，则用强度 I 乘以吸收层的厚度 d 得到的曲线会在厚度 d 为某一特定值时达到一个最大值。如果射线包含两个穿透力不同的成分，则在原始曲线的强度值上乘以吸收层的厚度之后，曲线上就会出现两个最大值（让我们把这条曲线称作变形后的曲线）。当我们把自己的实验结果用这种方式处理时，从得到的曲线上可以看出，大气中的辐射包含两个或三个穿透力不同的成分。

英文

我们也可以用实验方法来确认对辐射成分的分解是否是正确的。当我们用一个开放的电离室测量自由大气中的射线强度时，我们还用刚刚用过的数学方法来处理。普通的辐射强度曲线是用包含一个大气压空气的电离室得到的。当我们用一个开放电离室做试验时，我们会发现电离

室中的电流值小于在同样比例的空气压力下——同时也是电离室中的压力下的电流值，也小于常压下的电流值。这样我们就直接得到了一个变形的电离曲线，因为压力与射线透过的物质层的质量成正比。 英文

我们用这样的电离室做了两次实验，结果都不十分令人满意。第一次实验使用的电离室太小（体积仅为22升），因而灵敏度不够高；第二次实验所用的电离室体积为105升，这样灵敏度就足够高了。8月30日得到的照相纪录给出了很好的结果，但不幸的是，这个装置的温度降到了 -20°C 以下，因而所需的校正值略大于正常值。对于我们的气球来说，这个装置已经很重了（3.7千克），所以我们没有安装抵御冷气的防护设施。但根据测量结果绘制的曲线（图2）仍然会好于密闭电离室得到的结果，并且与用上述方法计算出来的变形曲线吻合得很好。在变形的曲线中也可以看到第二个最大值，但是，这个最大值并不是很明显，我们将设法确保更有利的实验条件，尽可能地避免各种修正。我认为曲线的这个部分对于我们分析和解释这条曲线至关重要。 英文

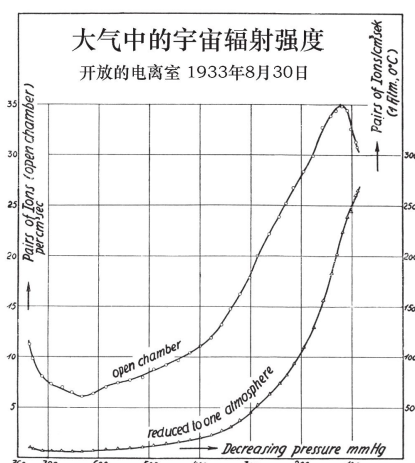


图2. 英文

一般而言，如果我们想得到一条从海平面到大气层顶部的完整曲线，用开放电离室进行测量是很方便的，因为开放电离室的观测值只在1到5之间变化，而封闭电离室的测量值则会从1一直变化到150。因此，在图2中，开放电离室的标准强度曲线在较低部分会比密闭电离室的更精确，密闭电离室标准曲线上的值是由开放电离室的值乘以 p_0/p 得到的。 英文

我要感谢奥尔先生在测量中给我的帮助，以及“德国科学临时学会”对这项研究工作的支持。 英文

（刘霞 翻译；马宇蓓 审稿）

* 这篇论文曾在英国科学促进会A分会（数学和物理学分会）于9月8日在莱斯特举行的会议上被宣读过。

Interaction of Hard γ -rays with Atomic Nuclei

Two Chinese physicists from the National Tsing Hua University here describe experiments in which hard gamma rays kick electrons out of lead or aluminium. They suggested that the data imply some kind of nuclear disintegration triggered by the gamma rays. However, as Ernest Rutherford notes in a short addendum to the paper, the authors had sent him a letter along with their paper clearly indicating that they had not yet heard about recent results demonstrating the creation of electron-positron pairs from energetic gamma rays in the strong field in the vicinity of the atomic nucleus. This process of pair creation, he suggests, might well provide a more natural explanation for the experimental results.

中文

IT is known that when a pencil of hard γ -rays of thorium-C" passes through lead, in addition to the absorption by electrons of the shell, there exists a type of nuclear absorption, accompanied by the emission of characteristic radiations of frequencies different from the primary¹. The intensity of such radiations has been estimated, and it has been found that the total energy of the characteristic radiations emitted is much smaller than the total energy of the primary radiation absorbed by the nuclei². This would be expected, if we assume that a nuclear disintegration occurs in such a process, so that a part of the absorbed energy is spent. From this point of view, we have tried to detect electrons which might be ejected from the lead nuclei by the primary

In our experiment, the γ -ray source was a radium–thorium preparation equivalent to 10 mgm. of radium. Two Geiger–Müller counters, one having an aluminium wall and the other a lead wall, were used. The counters had equal inner dimensions and approximately equal mass per square cm. of the wall (that is, 0.92 mm. thick for the aluminium counter and 0.22 mm. thick for the lead counter). Let N_{Al} and N_{Pb} be the number of electrons produced in equal time intervals by a given beam of γ -rays in the aluminium and lead counters respectively. The ratio $N_{\text{Pb}}/N_{\text{Al}}$ as a function of the wave-length λ of the incident γ -radiation will at first decrease with decreasing λ , due to the diminishing photoelectric absorption of lead. As the wave-length further decreases, the ratio $N_{\text{Pb}}/N_{\text{Al}}$ might, however, rise again, if the heavy lead nuclei begin to be disintegrated by γ -quanta of wave-length less than a certain value and the electrons ejected from the lead nuclei in the disintegration process add themselves to N_{Pb} . 中文

By using a beam of γ -rays of thorium-C" filtered through 2 cm. of lead and scattered by iron at different angles, we measured the ratios $N_{\text{Pb}}/N_{\text{Al}}$ for γ -rays of different wave-lengths. The experimental result is shown in the accompanying table, where $N_{\text{Pb}}/N_{\text{Al}}$ is multiplied by a constant k such that the value $kN_{\text{Pb}}/N_{\text{Al}}$ is unity for the scattered radiation at 23° . 中文

	$\lambda(\text{x.u.})$	$kN_{\text{Pb}}/N_{\text{Al}}$
Primary radiation	4.7	1.16 ± 0.04
Scattered radiation at 23°	6.6	1.00
Scattered radiation at 46°	12.1	1.23 ± 0.08

中文

In the table, the ratio $N_{\text{Pb}}/N_{\text{Al}}$ for $\lambda = 6.6 \text{ x.u.}$ is seen to be smaller than that for $\lambda = 12.1 \text{ x.u.}$, and for $\lambda = 4.7 \text{ x.u.}$ it again rises as was expected if electrons were ejected from the lead nuclei by the hard radiation. The difference of the two ratios for $\lambda = 4.7 \text{ x.u.}$ and 6.6

x.u. is about 16 percent. Now, the increase of the ratio $N_{\text{Pb}}/N_{\text{Al}}$ for $\lambda = 4.7$ x.u. might also result from a difference in the scattering effect of the lead nuclei and aluminium nuclei towards the Compton recoil electrons produced in the counter walls by the incident γ -rays. If this were the case, the difference of the ratios for $\gamma = 6.6$ x.u. and 4.7 x.u. should be more pronounced by using counters of thicker walls, since the effect of scattering increases with thickness of the wall. But the same result, namely, a difference of about 16 percent between the two ratios, was obtained when the experiment was repeated with a lead counter with walls 0.3 mm. thick and an aluminium one with walls 1.2 mm. thick. Therefore the above result seems to support the view that the lead nuclei are disintegrated by the hard γ -rays. [中文](#)

The details of the experiment will be published elsewhere. [中文](#)

C. Y. Chao and T. T. Kung

* * *

It is obvious from a letter to me which accompanied the above communication that Prof. Chao and Mr. Kung have not yet heard of the recent work concerning the positive electron, and in particular of the creation of a pair of electrons, a negative and a positive, by the conversion of a γ -ray of high energy in the strong electric field of a nucleus. The experiments they describe provide valuable additional evidence of this phenomenon, and would doubtless have been interpreted by them in this way rather than as a nuclear disintegration. It is interesting to note that the magnitude of the effect is about the same as is found in other experiments. [中文](#)

Rutherford

(132, 709; 1933)

References:

1. Chao, *Phys. Rev.*, **33**, 1519 (1930); Gray and Tarrant, *Proc. Roy. Soc., A*, **136**, 662 (1932).
2. Gray and Tarrant, *Proc. Roy. Soc., A*, **136**, 662 (1932). Chao, *Science Reports of National Tsing Hua University*, 1st series, **1**, 159 (1932).

硬 γ 射线和原子核的反应

两位来自国立清华大学的中国物理学家在文中介绍了他们用硬 γ 射线将铅和铝中的电子轰击出来的实验。他们认为实验数据说明 γ 射线引发了某种形式的核衰变。然而，欧内斯特·卢瑟福在这篇论文后面的简短评论中指出：从作者随论文邮寄给他的一封信中可以明显看出，他们还不知道最近的一项研究成果，即在原子核附近的强场中，高能 γ 射线会产生电子-正电子对。卢瑟福认为用产生正负电子对来解释两位中国物理学家的实验结果也许会显得更合理一些。

英文

众所周知，当一束由钷C¹⁴⁷放射出的硬 γ 射线穿过铅时，除了出现铅的外层电子对 γ 射线的吸收以外，还会出现铅原子核对 γ 射线的吸收，并伴随着发出和初级辐射具有不同频率的特征辐射^[1]。这种特征辐射的强度已经被估算过了，即放射出的特征辐射的总能量远远小于被原子核吸收的初级辐射的总能量^[2]。我们可以预见，如果假设原子核在这一过程中发生了衰变，那么原子核吸收的一部分能量就会在此过程中被消耗掉。从这种观点出发，我们测量了由初级 γ 粒子从铅原子核中打出来的电子。

英文

我们在实验中采用的 γ 射线源是镭-钷合成的放射源，相当于10毫克的镭放射源。所使用的两个盖革-缪勒计数器，一个是铝壁，另一个是铅壁。两个计数器具有相同的内壁尺寸，并且每平方厘米壁的质量也大约相等（即0.92毫米厚的铝计数器和0.22毫米厚的铅计数器）。用 N_{Al} 和 N_{Pb} 分别表示在相同的时间间隔内，由给定的 γ 射线在铝计数器和铅计数器中产生的电子数目。比值 N_{Pb}/N_{Al} 是入射 γ 射线波长 λ 的函数，在开始阶段由于铅的光电吸收不断减弱，所以将会随着 λ 的减小而减小。然而，当波长 λ 进一步减小时，比值 N_{Pb}/N_{Al} 可能反而会变大。这是因为波长小于某个特定值的 γ 粒子可能会引起重铅核的衰变，在铅核衰变过程

中放射出来的电子会增加 N_{Pb} 的值。 [英文](#)

将一束由钷C¹⁴⁷放射出的 γ 射线用2厘米厚的铅板过滤，再经过铁散射到不同的方向，我们测量了对应不同波长 γ 射线的 $N_{\text{Pb}}/N_{\text{Al}}$ 比值。下表中给出了相关的实验结果，其中 $N_{\text{Pb}}/N_{\text{Al}}$ 要乘以一个常数 k ，这样，我们把辐射射线散射角度为23°时的 $kN_{\text{Pb}}/N_{\text{Al}}$ 值作为单位1。 [英文](#)

	λ (10^{-11} 厘米)	$kN_{\text{Pb}}/N_{\text{Al}}$
初级辐射	4.7	1.16 ± 0.04
辐射散射角为 23°	6.6	1.00
辐射散射角为 46°	12.1	1.23 ± 0.08

[英文](#)

在上面的表格中， $\lambda = 6.6 \times 10^{-11}$ 厘米时的 $N_{\text{Pb}}/N_{\text{Al}}$ 值小于 $\lambda = 12.1 \times 10^{-11}$ 厘米时的相应值，而当 $\lambda = 4.7 \times 10^{-11}$ 厘米时，如我们所预料的那样，硬 γ 射线引发铅核放射出电子，从而使 $N_{\text{Pb}}/N_{\text{Al}}$ 值增大。这个比值在 $\lambda = 4.7 \times 10^{-11}$ 厘米时与 $\lambda = 6.6 \times 10^{-11}$ 厘米时相差大约16%。也许有人认为，当 $\lambda = 4.7 \times 10^{-11}$ 厘米时比值 $N_{\text{Pb}}/N_{\text{Al}}$ 的增加还有可能是由于铅核和铝核对入射 γ 射线在计数器管壁上产生的康普顿反冲电子的散射效应的差别导致的。如果真是这样的话，那么 $\lambda = 6.6 \times 10^{-11}$ 厘米和 4.7×10^{-11} 厘米时的 $N_{\text{Al}}/N_{\text{Pb}}$ 值之差在使用管壁较厚的计数器时应该更加显著，因为散射效应会随着管壁的增厚而增强。但是，当我们使用壁厚为0.3毫米的铝计数器和壁厚为1.2毫米的铝计数器重复上面的实验时，我们得到了相同的结果，也就是两个 $N_{\text{Pb}}/N_{\text{Al}}$ 比值之间仍相差约16%。这样看来，以上结果支持了硬 γ 射线引发铅核发生衰变的观点。 [英文](#)

实验的具体细节将发表在其他地方。 [英文](#)

赵忠尧，龚祖同

* * *

在与以上这篇通讯一块寄给我的信中可以明显看出，赵教授和龚先生还不知道最近关于正电子的研究工作，特别是关于在一个原子核的强电场中，高能 γ 射线可以转化产生一对电子，即一个正电子和一个负电

子的情况。他们描述的实验又一次为这一现象提供了非常有价值的证据，毫无疑问，该实验现象应该被他们解释为高能 γ 射线产生了正负电子对，而不是原子核的衰变。值得注意的是，这一效应的强度与在其他实验中观测到的强度大致相同。

[英文](#)

卢瑟福

（王静 翻译；尚仁成 审稿）

A Suggested Explanation of β -ray Activity

M. N. Saha and D. S. Kothari

Radioactive beta decay had proven most baffling. Unlike alpha particles, beta particles were emitted not with a well-defined energy, but with a broad range of energies, and physicists had established that these energies were created in the nuclear process itself, not as the electron interacted with shell electrons. Here Indian physicists Meghnad Saha and Daulat Singh Kothari suggest that the mystery might be settled by the recently discovered process in which a gamma photon can create an electron and its antimatter partner, a positron. The electron so created might have any kinetic energy, depending on the photon's energy. This attempted explanation seemed promising, though physicists still knew nothing of the weak nuclear force or of neutrinos, which a proper explanation would require. [中文](#)

THE β -ray activity of radioactive bodies has until now proved to be a very baffling problem. The points at issue are summarised in Gamow's "Constitution of Atomic Nuclei", etc. (pp. 52–54), and in "Radiations from Radioactive Bodies" by Rutherford, Chadwick and Ellis (p. 385). They are also discussed at some length by Bohr in his Faraday lecture (1930). [中文](#)

Briefly speaking, the chief points under discussion are the following:

the disintegration electrons (β -rays) from a radioactive body are not emitted with a single velocity as in the case of α -rays, but show a distribution of velocities over wide ranges, though the breaking-up of the atom is a unitary process, as is proved by the fact that the life-period is definite and there is one electron for each disintegrating atom. It has further been proved that the continuous distribution of velocities is a nuclear process, and not due to action of the surrounding shell of electrons. 中文

It appears that the β -ray disintegration admits of a very simple explanation on the basis of the recent experiments by Anderson and Neddermeyer, and Curie and Joliot on the production of positrons by the impact of hard γ -rays with the nuclei of elements. These experiments have been interpreted by Blackett and Occhialini as indicating the conversion of a γ -ray quantum into an electron and a positron near the nucleus. Curie and Joliot have brought further evidence in favour of this view by showing that γ -rays of thorium C" (energy 2.6×10^6 electron volts) are converted inside all matter into an electron (mass 9×10^{-28} gm., energy $m_0 c^2 = 0.51 \times 10^6$ eV) and a positron (having the same mass and energy as the electron), the excess energy being distributed as the kinetic energy of the two particles, and the energy of the residual quantum. They have denoted this phenomenon by the term "materialisation of light quanta". They have further shown that a proton is a complex structure, being a compound of the neutron and a positron. As pointed out by Blackett and Occhialini, this explains the anomalous absorption of γ -ray quanta observed by Gray and Tarrant, which Gentner has found to commence with the γ -ray possessing the limiting energy 1.1 million electron volts. 中文

The discovery, which is confirmed by so many workers, promises to be of great importance, as it establishes for the first time, on experimental grounds, the splitting up of a quantum into two charged

particles of opposite sign. Many astrophysicists have postulated the probability of the annihilation of the proton and the electron with their mass energies converted into quanta, but the actual process, as revealed by these experiments, seems to be very different. For the quantum breaks up into charged particles possessing opposite charges, but having equal mass, and the positron being absorbed by the neutron forms the proton which is thus seen to be complex. The phenomenon is therefore not a “materialisation of the quantum” as Curie and Joliot suggest, for the neutron appears to be the fundamental mass-particle, but it consists in a splitting of the quantum into two fundamental opposite charges. We may call it “electro-division of the quantum”. [中文](#)

Let us see how we can explain β -ray activity. If the “electro-division of a quantum” can be brought about by a nucleus when the quantum hits it from the outside, it is much more probable that the γ -rays produced within the nucleus itself should be completely split up into an electron and a positron. The electron will come out as a β -ray, but a positron will not be able to come out if the conversion takes place within the potential barrier. It will attach itself mainly to some one of the numerous neutrons which are present in the nucleus, and thus form a proton. The positive charge of the nucleus will therefore be increased by unity. [中文](#)

It is not difficult to explain the continuous distribution of β -ray energy. The γ -ray may suffer this “internal electro-division” anywhere within the nucleus, and hence the velocities imparted to the resulting electrons may vary within wide limits. The exact mathematical calculation can be carried out only when more data are forthcoming. The positron combining with the neutron will give rise to the softer γ -rays which are always present in a β -ray disintegration. [中文](#)

According to the above view, the β -ray emission is only a secondary process, the primary phenomenon which starts this chain of events

being the generation of a primary γ -ray. We can now ask ourselves: How is this γ -ray generated? It must be due to the passage of an α -particle or proton from one barrier to another. Gamow, and also Condon and Gurney have postulated the existence of only one barrier in a radioactive nucleus for explaining the emission of α -rays, with definite velocity, but several lines of argument indicate that there may be more than one barrier present in the nucleus. When an α -particle crosses from one barrier to the other, the γ -ray responsible for the whole chain of events leading to the β -ray disintegration is emitted. The life-period is therefore determined by the time of leakage of an α -particle or proton from one barrier to another, and this explains why the life-periods of β -ray bodies are of the same order as those of α -ray bodies, and have a definite value. 中文

(132, 747; 1933)

M. N. Saha and D. S. Kothari: Department of Physics, Allahabad University, Oct. 20.

β 射线放射性的一种可能的解释

梅格纳德·萨哈，道拉特·科塔里

放射性 β 衰变是最令人困惑不解的。与 α 粒子不同， β 粒子的能量不是固定的，而是存在一个很宽的范围，物理学家们已经证实这些能量是核过程本身产生的，并非电子与壳层电子相互作用的结果。两位印度物理学家梅格纳德·萨哈和道拉特·辛格·科塔里在本文中提出：由于最近发现 γ 光子可以产生一个电子和它的反粒子——正电子，这个谜有可能会随之得到破解。在这个过程中产生的电子也许会具有一定的动能，这取决于光子的能量。这种尝试性的解释看似前景光明，但那时的物理学家对弱核力和中微子仍一无所知，而只有了解了弱核力和中微子，才能得到这个问题的正确解释。

[英文](#)

放射性物质的 β 射线放射性一直以来都是一个非常令人困惑不解的问题。在伽莫夫的《原子核的结构》（第52~54页）及卢瑟福、查德威克和埃利斯的《放射性物质的辐射》（第385页）等著作中都总结了一些有争议的论点。玻尔在法拉第讲座（1930年）中也对这些观点进行了详细的讨论。

[英文](#)

简言之，争论的主要方面是：原子有确定的衰变寿命以及每个发生衰变的原子发射一个电子这些事实已经证明原子的衰变是一个单一的过程，但是由放射性物质放射出的衰变电子（ β 射线）并没有像 α 射线那样具有单一的速度，而是出现了速度分布在一个很大范围内的情况。人们还进一步证明了速度的连续分布与核过程有关，而与核外电子壳层的作用无关。

[英文](#)

最近，安德森、尼德迈耶以及居里、约里奥进行了硬 γ 射线轰击原子核产生正电子的实验，在此基础之上看似可以给出关于 β 衰变的一个

非常简单的解释。布莱克特和奥基亚利尼对这些实验的解释是：一个 γ 粒子在原子核附近转化成了一个负电子和一个正电子。居里和约里奥为这个观点提供了进一步的证据，他们的实验表明钍C''的 γ 射线（能量为 2.6×10^6 电子伏特）在所有的材料中都会转化为一个负电子（质量为 9×10^{-28} 克，能量为 $m_0c^2 = 0.51 \times 10^6$ 电子伏特）和一个正电子（质量和能量与负电子相同），多余的能量除了分配给正负两个电子作为动能外，还将分配给剩余的量子，他们把这种现象称为“光量子的物质化”。他们进一步指出，质子具有复杂的内部结构，包括一个中子和一个正电子。布莱克特和奥基亚利尼指出，格雷和塔兰特观察到的反常 γ 射线吸收也能用此进行解释，但根特纳发现，能量在1.1百万电子伏特以上的 γ 射线才能发生这种反常吸收过程。 [英文](#)

这个发现已经被很多研究人员所确认，当然也必定有着非常重大的意义，因为这是第一次在实验基础上确立：一个量子可以劈裂成两个带有相反电荷的粒子。很多天体物理学家都认为一个质子和一个电子有可能会发生湮灭并且将其质能转化为量子，但是实际的过程，正如在实验中所看到的那样，是很难发生的。因为一个量子会分裂成一对带相反电荷但质量相等的粒子，并且其中的正电子会被中子吸收形成质子，由此可以认为质子具有复杂的结构。因此，这个现象并不是居里和约里奥所说的“量子的物质化”过程，因为中子看似一个有质量的基本粒子，但是它却存在于量子分裂成两个电量相反的电荷的过程中。我们可以把这个过程称为“量子的电分离”。 [英文](#)

那么，让我们来看看 β 射线的放射性该如何解释。如果外部量子轰击原子核时会引发“量子的电分离”，那么在该原子核内部产生的 γ 射线更有可能完全分裂成一个负电子和一个正电子。电子将以 β 射线的形式发射出来，但是如果这个分裂过程发生在势垒当中，那么正电子就不能被发射出来。正电子将和存在于原子核中的大量中子当中的一个相结合，形成一个质子。这样，原子核的正电量将因此增加一个单位。

[英文](#)

而 β 射线能量的连续分布也不难解释。 γ 射线可以在原子核中的任意位置发生“内部电分离”，这样， γ 射线转化产生的电子的速度就会在很宽的范围变化。只有得到更多的实验数据，我们才能进行严格的数学计

算。和中子结合的正电子将产生软 γ 射线，这种软 γ 射线经常出现在 β 衰变反应中。 [英文](#)

根据上面的观点， β 射线的发射只是一个二级过程，初级 γ 射线的产生才是引发这个反应链的最初原因。现在我们可以问问自己：这种 γ 射线是如何产生的呢？一定是因为一个 α 粒子或者一个质子从一个势垒穿越到另一个势垒而产生的。伽莫夫以及康登和格尼曾经以放射性原子核中只存在一个势垒出发解释了具有确定速度的 α 射线的放射，但是一些争论表明，原子核中可能会有不止一个势垒。在一个 α 粒子穿越一个势垒来到另一个势垒的过程中产生了引发 β 衰变链的 γ 射线。所以 β 射线放射性的周期取决于 α 粒子或质子从一个势垒到另一个势垒所用的时间，这就解释了为什么 β 射线的寿命周期和 α 射线的寿命周期有相同的量级并且有确定量值。 [英文](#)

（王静 翻译；尚仁成 审稿）

Latitude Effect of Cosmic Radiation

J. A. Prins

Earlier experiments by Jacob Clay, Arthur Compton and others had suggested that the flux of cosmic rays has a minimum close to the equator. Here J. A. Prins reports results measured using an ionisation chamber carried by the S.S. *Springfontein* during a voyage from Holland to South Africa, which also showed a clear minimum near the equator. Unfortunately, he says, his apparatus had broken down, and he could not gather data from southern latitudes, which might have helped clarify an apparent difference noted by other researchers between the flux in the two hemispheres. But the results did suggest that most cosmic rays were charged particles, which would be influenced by the Earth's magnetic field and find penetration easiest near the poles. [中文](#)

IT was found for the first time by Clay¹ on voyages between Holland and Java that the intensity of cosmic radiation has a minimum in the neighbourhood of the magnetic equator. The extensive survey directed by Compton² confirmed the existence of this "latitude effect" and showed it to be more pronounced at higher altitude. More accurate results at sea-level are due to an investigation of Clay and Berlage³. As this again refers to the line from Holland to Java, I thought it would be worth while to perform analogous measurements on a trip from

Holland to South Africa. During this investigation Hoerlin⁴ published results he obtained on the line Peru–Strait of Magellan–Hamburg. These results and those of the other authors as given by Clay are represented in Fig. 1 by continuous curves, my own results by open circles. Clearly the latter lie somewhat closer to Clay’s curve than to Hoerlin’s. 中文

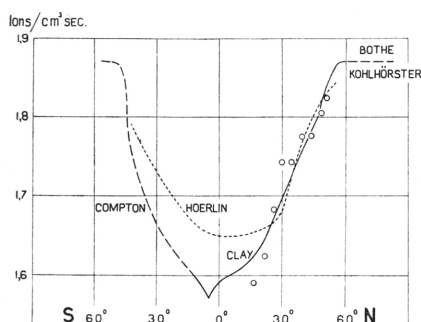


Fig. 1. Latitude effect of cosmic radiation. Circles indicate results of author. Vertical scale indicates number of pairs of ions in normal air. 中文

Unfortunately, my apparatus broke down in the tropics, so I have not been able to get evidence on the remarkable difference between the southern and northern hemispheres as indicated by Hoerlin’s results. Though we may feel satisfied that an equatorial minimum of the same order of magnitude is found by all investigators (indicating that the cosmic radiation consists largely of a cosmic rain of charged particles) it would seem that an accurate repetition of this kind of measurement to obtain the exact shape of the curve is not superfluous. 中文

Regarding my observations, the following particulars may be given. The ionisation chamber had a volume of 3 litres and contained argon at a pressure of 30 atm. It was shielded by 8 cm. of iron and was placed in a hut on board the S.S. *Springfontein* of the Holland Africa line, the deck over it being of negligible thickness. The wall of the ionisation chamber was brought to 120 v. and the ionisation current collected on an insulated rod connected to a Lindemann electrometer and to a small capacity (4 cm.). To start an observation, the earthing

key of the rod was opened and a stop-watch set running at the same moment. The electrometer was kept at zero by gradually applying a potential to the capacity so as to compensate the charge due to the ionisation current. After some time (about 6 min.) the potential (about 3 v.) was read on a voltmeter. From this the number of ions produced in the chamber per cm.³ per sec. may be deduced, assuming saturation. This number is called the “intensity” of cosmic radiation. A small correction for barometric pressure was applied to it (2.4 percent for 1 cm. mercury). In the graph in Fig. 1 these values (like those of Hoerlin) have been multiplied by such a factor (1/33.2) as to make the value at 50° coincide with the value given by Clay for normal air.

中文

I wish to thank the Groninger Universiteitsfonds for a grant of money, Prof. Coster for allowing the apparatus to be made in the workshop of his laboratory, Prof. Clay for some kind advice and finally the directors of the Holland Africa line and the crew of the S.S. *Springfontein* for their kind collaboration.

中文

(132, 781; 1933)

J. A. Prins: Natuurkundig Laboratorium der Rijks-Universiteit, Groningen, Oct. 19.

References:

1. Clay, J., *Proc. Amsterdam*, **30**, 1115 (1927); **31**, 1091 (1928).
2. Compton, A. H., *Phys. Rev.*, **43**, 387 (1933).
3. Clay, J., and Berlage, H. P., *Naturwiss.*, **20**, 687 (1932); Clay, J., *Naturwiss.*, **21**, 43 (1933).
4. Hoerlin, H., *Nature*, **132**, 61 (July 8, 1933).

宇宙射线的纬度效应

约翰·普林斯

雅各布·克莱、阿瑟·康普顿和其他人的早期实验曾经说明宇宙射线的通量在靠近赤道处有一个最小值。本文中，普林斯报告了他在从荷兰开往南非的斯普林方廷号远洋轮上利用装载于船上的电离室测量得到的结果，该结果同样说明在赤道附近会出现一个最小值。他说，不幸的是他的仪器坏了，所以没有能够收集到南纬的数据，这使他失去了一个证明其他研究人员所指出的宇宙射线在南北半球的通量存在明显不同的机会。但他的结果确实表明了大多数的宇宙射线都是带电粒子，它们会受到地球磁场的影响，而且在两极附近最易穿透。 [英文](#)

克莱^[1]在往返于荷兰和爪哇之间的旅行中首次发现宇宙射线的强度在地磁赤道附近存在一个最小值。康普顿^[2]通过广泛的调查证实了“纬度效应”的存在，并发现高纬度地区这种效应会更明显。克莱和贝尔拉赫^[3]在海平面上进行测量得到了更为精确的结果。考虑到他们的调查也是在从荷兰至爪哇的航线上进行的，我认为有必要在从荷兰到南非的航线上进行类似的测量，以便于比较。就在我做这个实验的同时，霍尔林^[4]发表了他在秘鲁-麦哲伦海峡-汉堡一线测量得到的结果。这些结果连同克莱给出的其他人的结果都画在图1中，用连续曲线代表；我的结果用空心圆圈表示。把我的结果分别与克莱和霍尔林的结果相比较后发现：我的结果与克莱的结果更接近。 [英文](#)

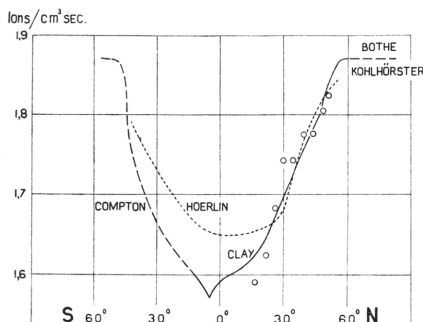


图1．宇宙射线的纬度效应。圆圈代表作者的结果，纵坐标表示在标准大气中产生的离子对数量。 [英文](#)

不幸的是，进入热带地区以后我的仪器失效了，因此，我无法验证在霍尔林的结果中所指出的南北半球间的明显差异。虽然我们对所有调查者都发现在赤道附近宇宙射线存在同量级的最小值感到满意（这表明宇宙射线主要是由一系列宇宙中的带电粒子组成的），但精确地重复进行此类测量以得到该曲线的准确形状仍然是有必要的。 [英文](#)

以下是我的观测过程。电离室的容积为3升，里面充有30个标准大气压的氩气。在用8 cm厚的铁板屏蔽后，电离室被放在往返于荷兰—非洲航线的斯普林方廷号远洋轮上的一个小屋里，铁板屏蔽上方的甲板厚度相对而言可忽略不计。电离室的壁上加有120伏的电压，在一根与一个林德曼静电计和一个小电容（4 cm）相连的绝缘棒上收集电离电流。在开始观测之前，先打开绝缘棒的接地开关，同时开始用跑表计时。为了保持静电计的示数为零，需要不断增加电容上的电压以补偿由于电离电流引起的电荷变化。过一段时间（大约6分钟）再读出电压表上的电位值（约为3伏）。假定这时已经达到了饱和状态，则由此可以推算出电离室中每秒每立方厘米产生的离子数，这个数被称为宇宙射线的“强度”。我对气压表的压力进行了小的修正（1 cm汞柱修正了2.4%）。为了使纬度为50°时的值与克莱在标准大气中得到的值一致，图1曲线上的这些值（和霍尔林的结果类似）都已经乘上了这样的一个因子（1/33.2）。 [英文](#)

我要感谢格罗宁根大学基金会给予的资助，感谢科斯特教授让我在他的实验室中制作仪器，感谢克莱教授为我提供了一些好的建议，最后我还要感谢荷兰—非洲航线的负责人以及斯普林方廷号上全体船员的积

极配合。 英文

(刘霞 翻译；马宇蓓 审稿)

The Positive Electron

P. M. S. Blackett

The discovery of the positive electron, although consistent with Dirac's theory of electrons, created problems for nuclear physicists eager for a plain account of how positive electrons are generated—most often by the interaction of energetic γ -rays with heavy particles or even atomic nuclei. Blackett's approach to the problem in this article is very much that of an experimentalist: how best to explain the fragmentary experimental data so far accumulated about positrons. 中

文

THE discovery of the positive electron arose from the study of cosmic radiation by the cloud method¹. Amongst the tracks of the particles of very great energy, associated with cosmic radiation, were found some which differed from the tracks of negative electrons only by being curved by a magnetic field in the opposite direction. Terrestrial sources of positive electrons of lower energy are now also available, since it has been found that they are produced when hard gamma rays are absorbed by matter, and also in certain cases of nuclear transformation. The production of positive electrons in the laboratory is therefore an easy matter. 中文

The charge and mass of a positive electron can be calculated from the ionisation it produces. For example, Anderson² has estimated that the difference between the ionisation due to fast positive and negative electrons with the same curvature in a magnetic field, is not as much

as 20 percent. Since for *very fast* particles the ionisation depends on the square of the charge but scarcely at all on the mass, the charge on a positive electron cannot differ by as much as 10 percent from that on a negative electron. On the other hand, for *slow* particles with given charge, the ionisation varies as the mass, so the same equality of ionisation indicates that the masses must be within 20 percent. To obtain further information as to the properties of positive electrons, it is convenient to study in detail the simplest case known of their production; namely, that in which a beam of homogeneous gamma rays is absorbed by heavy elements. [中文](#)

The well-filtered gamma radiation from thorium-C" is nearly homogeneous and has an energy of 2.62×10^6 volts. It has been found by Anderson and Neddermeyer³, by Curie and Joliot⁴ and by Meitner and Philipp⁵ that when such rays fall on a heavy element, positive electrons are ejected. [中文](#)

Positive electrons are also produced when the radiation from beryllium, bombarded by alpha rays, is absorbed⁶. Though this radiation is complex, consisting of neutrons together with gamma rays of rather more than 5.0×10^6 volts energy, Curie and Joliot⁶ have shown by absorption experiments that the positive electrons are certainly mainly due to the latter. [中文](#)

The following table, which is derived from the work of Curie and Joliot, Grinberg⁷, and some unpublished results of Chadwick, Blackett and Occhialini, gives the numbers of positive electrons ejected in a forward direction from different elements by various radiations, the numbers being expressed as a fraction of the observed number of negative electrons. These percentages give only a rough indication of the frequency of production of positive electrons, since the actual angular distributions are not known, and since the effect of the particular experimental arrangement may be considerable. [中文](#)

Number of Positive Electrons produced when Gamma Rays are Absorbed.

Source	Energy of gamma ray	Absorber		
		U	Pb	Al
Ra	1.0 to 2.2×10^6 volts		3%	
ThC ⁺	2.62×10^6 volts		10%	very small
Po+Be	5 to 6×10^6 volts	more than 40%	40%	5%

中文

The ejected negative electrons comprise two groups, consisting of the photo-electrons with the whole energy of the quanta, that is with 2.62×10^6 volts, and the Compton electrons which have a maximum energy of 2.39×10^6 volts in a forward direction. The table shows that the number of positive electrons increases rapidly with the energy of the quanta and with the atomic number of the absorber. 中文

If from these figures the effective area of a heavy atom for the production of a positive electron by a quantum of 5×10^6 volts is calculated, values are found which are rather larger than the area of cross-section of the nucleus. This fact makes it improbable that the production of the positive electrons is mainly a nuclear phenomenon.

中文

This view is strengthened by consideration of the energies of the particles. The maximum energy of the positive electrons produced by a given radiation appears to be about the same for all absorbers. If the particles had a nuclear origin, a variation with the type of nucleus would be expected. 中文

For the 5.0×10^6 and the 2.62×10^6 volt radiations, the maximum energies of the positive electrons are found to be about 4 and 1.6×10^6 volts respectively, that is, in each case about a million volts less than the energy of the quantum. 中文

If the positive electrons are indeed produced outside the nucleus, many important conclusions follow:

(a) Since there is certainly no room, in atomic theory, for the permanent existence of positive electrons well outside a nucleus, then a positive electron that comes from there must be born there, and if born there, an equal negative electron must be born simultaneously in order to conserve electric charge. This is confirmed by the experimental observation that pairs of tracks do occur, which almost certainly are to be interpreted as due to the simultaneous ejection of a positive and a negative electron. 中文

To produce such a pair of electrons with opposite charges requires an expenditure of energy $(m_1 + m_2)c^2$. If both particles have the electronic mass, this energy amounts to 1.01×10^6 volts, so that in the case of the 2.62×10^6 volt radiation, no pair of positive and negative electrons can have more energy than 1.61×10^6 volts energy. Anderson has found this to be the case. Again, the maximum energy of a single positive electron producing an unpaired track should also be 1.61×10^6 volts. An experimental determination of this maximum energy is being made by Chadwick, Blackett and Occhialini, and their preliminary results* give the value of $1.58 \pm 0.07 \times 10^6$ volts, in excellent agreement with the theory. 中文

(b) The positive electron must have a spin of $\frac{1}{2}$ and so obey the Fermi-Dirac statistics. For since energy is observed to be conserved during the birth process, it is to be expected that linear and angular momentum are also conserved. So if a quantum gives rise to a pair of particles, one of which has a spin of $\frac{1}{2} \frac{h}{2\pi}$, the other must have the same spin, since a quantum can only excite changes for which the angular momentum changes by 0 or 1. The argument is still valid even if possible changes in the nuclear spin are taken into account, for these must also be integral. 中文

(c) A necessary consequence of the occurrence of the process whereby a quantum interacts with an atom to produce a pair of electrons of opposite sign, is the occurrence of the reverse process, in which a

positive electron and a negative electron interact with each other and the field of an atom to produce a single quantum of radiation. Since the conditions for this occurrence cannot be rare, a positive electron cannot be expected to exist for more than a short time in matter at ordinary densities. [中文](#)

These conclusions as to the existence and the properties of positive electrons have been derived from the experimental data by the use of simple physical principles. That Dirac's theory of the electron predicts the existence of particles with just these properties, gives strong reason to believe in the essential correctness of his theory. [中文](#)

Dirac succeeded in formulating the wave equation for an electron moving in a potential field in such a way as to make it relativistically invariant. The solution of this new wave equation not only led, in the case of the hydrogen atom, to a complete explanation of the fine structure of the spectral lines, but also to a rational explanation of the spin and magnetic moment of the electron itself. [中文](#)

However, in addition to the solutions corresponding to the normal electronic levels found experimentally, were others which seemed to correspond to no observed facts. These solutions seemed to predict the existence of states in which the electrons possessed a negative kinetic energy, and therefore did not correspond to particles in any usual sense. These states could not be ignored, because transitions must theoretically occur between them and the normal states corresponding to positive kinetic energy. Dirac suggested that the difficulty might be avoided if it were supposed that all the negative energy states are normally occupied, and further, that the totality of electrons in such states produce no external field. [中文](#)

On this view, only an unoccupied state or "hole" would correspond to an observed particle. It followed from the theory that such unoccupied states should behave in an external field like particles with the same

mass and spin as a negative electron but with a positive charge. The experimental discovery of the positive electron has therefore removed a very serious theoretical difficulty, and by so doing, has greatly extended the field of phenomena over which Dirac's theory may be applied. [中文](#)

Owing to analytical difficulties, the work of applying Dirac's theory to special cases has not progressed far, but Oppenheimer and Plesset⁸ have calculated approximately the probability of the production of pairs of electrons of opposite charge when hard gamma rays are absorbed by matter. So far as these theoretical results go, they are in rough agreement with the experimental conclusions, both as regards the order of magnitude of the effect and its dependence on the energy of the quantum and the atomic number of the absorber. [中文](#)

The calculations give for the extra absorption by lead and tin of the 2.62×10^6 volt radiation, due to the production of positive electrons, the values of 25 percent and 15 percent of the absorption by the normal scattering and photoelectric processes. These figures are roughly those observed experimentally by Tarrant and Gray. So one may conclude that a large part of the anomalous absorption may be attributed to the production of positive electrons. [中文](#)

One would expect that the absorbed energy would be re-radiated in two ways. An ejected positive electron may disappear by the reverse process to that which produced it, that is, by reacting with a negative electron and a nucleus, to give a single quantum of a million volts energy (see (c) above). Or it can disappear, according to Dirac's theory, by another type of process, in which a positive electron reacts with a *free* or *lightly bound* negative electron so that both disappear with the emission of two quanta of half a million volts energy.[†] It is remarkable that the re-emitted radiation is estimated by Gray and Tarrant to be composed mainly of just these two energies, of one half and one million volts. However, Fermi and Uhlenbeck⁹ have found

that the theoretical intensity of the hard component is far smaller than that observed. [中文](#)

This absorption of hard gamma rays by atoms, resulting in the production of pairs of oppositely charged electrons, may be thought of as a photoelectric absorption by the “virtual” electrons, that is, by electrons with negative kinetic energy, near the nucleus. According to Beck¹⁰, these virtual electrons may be considered to have a binding energy of the order of $2 mc^2$. Beck also shows that the number of these virtual electrons which are effective for the absorption are proportional to the square of the atomic number and that they amount to about one for each lead atom. The theory also indicates that the birth process takes place within a distance of $h/2\pi mc = 3.85 \times 10^{-11}$ cm. of the nucleus, that is, well inside the *K* ring. [中文](#)

Curie and Joliot¹¹ have found that positive electrons are produced when *aluminium* and *boron* are bombarded by alpha particles, and that these positive electrons have a higher energy than the accompanying negative electrons. *Silver*, *lithium* and *paraffin*, however, give no positive electrons. Curie and Joliot suggest that the positive electrons originate in the disintegrating nucleus, but it seems possible that they may be produced mainly outside the nucleus by the internal conversion of a gamma ray emitted by the nucleus. To explain the effect in this way, the probability of internal conversion must be nearly unity.‡ The greater energy of the positives may be explained by the fact that a positive electron gains kinetic energy and a negative electron loses it, on escaping from the field of a nucleus. This resulting difference in kinetic energy will be the larger the nearer to the nucleus that the pair is born, and so should be larger in the case of such an internal conversion process, which depends on a spherical wave, than in the usual case of external absorption, which depends on a plane wave. [中文](#)

Though it was in association with cosmic radiation that positive

electrons were first detected, the exact part they play in these complicated phenomena is not yet clear. But certain facts are established¹². (i) Of the fast particles which produce the cosmic ray ionisation at sea-level, about half are positive and half negative electrons. Their energies range from a few million to nearly 10^{10} volts. (ii) The same ratio is found in the “showers”. The showers appear therefore to represent the birth of multiple pairs of positive and negative electrons, as a result of one or more collision processes induced by the primary radiation. Dirac’s theory shows that the production of single pairs is of primary importance in the absorption of both gamma rays and particles of high energy¹³, but has, as yet, given no hint of the cause of the multiple pairs forming the showers. (iii) It has been shown that the majority of the particles incident on the earth’s atmosphere are positively charged¹⁴. 中文

Since protons are rarely observed at sea-level, it is probable that the positively charged incident particles are not protons but positive electrons. If this is so, the main part of the flux of cosmic radiation in inter-galactic space must be in the form of positive electrons; and since the total mass of this radiation has been estimated as possibly as large as 1/1,000 part of the mass of all the stars and nebulae¹⁵, it appears that the positive electron, though rare, because ephemeral, on earth, is an important constituent of the universe as a whole. 中文

(132, 917-919; 1933)

References:

1. Anderson, *Science*, **76**, 238 (1932). Blackett and Occhialini, *Proc. Roy. Soc., A*, **139**, 699 (1933).
2. Anderson, *Phys. Rev.*, **43**, 491 (1933). *Phys. Rev.*, **44**, 406 (1933).
3. Anderson and Neddermeyer, *Phys. Rev.*, **43**, 1034 (1933).
4. Curie and Joliot, *C. R. Acad. Sci.*, **196**, 1581 (1933).
5. Meitner and Philipp, *Naturwissenschaften*, **24**, 468 (1933).
6. Chadwick, Blackett and Occhialini, *Nature*, **131**, 473 (1933). Meitner and Philipp, *Naturwissenschaften*, **15**, 286 (1933). Curie and Joliot, *C.R. Acad. Sci.*, **196**, 405 (1933).

7. Grinberg, *C. R. Acad. Sci.*, **197**, 318 (1933).
8. Oppenheimer and Plesset, *Phys. Rev.*, **44**, 53 (1933).
9. Fermi and Uhlenbeck, *Phys. Rev.*, **44**, 510 (1933).
10. Beck, *Zeit. Phys.*, **83**, 498 (1933).
11. Curie and Joliot, *C. R. Acad. Sci.*, **196**, 1885 (1933).
12. Anderson, *Phys. Rev.*, **41**, 405 (1932); Kunze, *Zeit. Phys.*, **80**, 559 (1933); Blackett and Occhialini, *loc. cit.*
13. Furry and Carlson, *Phys. Rev.*, **44**, 237 (1933).
14. Johnson, *Phys. Rev.*, **43**, 1059 (1933).
15. Lemaitre, *Nature*, **128**, 704 (1931).

* The mass of the positive electron can be calculated from the equation

$$E_{\text{max.}} = h\nu - (m_1 + m_2)c^2$$

Using the values $h\nu = 2.62 \times 10^6$ volts, $E_{\text{max.}} = 1.58 \pm 0.07 \times 10^6$ volts.

We find

$$m_2 = (1.04 \pm 0.14)m_1.$$

This calculation affords probably the most accurate estimate of the mass of a positive electron yet available.

† Dirac's calculation of this annihilation probability gives a positive electron a life of less than 10^{-9} sec. in water, the life being inversely proportional to the density. If this predicted process is verified experimentally, it will be possible to assume the reverse process, the creation of a pair of electrons of opposite sign by the collision of two quanta of high energy. This latter process would then be the first case known of the "interference" of quanta; it is conceivable that this process has considerable cosmological importance.

‡ Oppenheimer and Plesset (*loc. cit.*) predict theoretically far smaller values.

正电子

帕特里克·布莱克特

正电子的发现虽然和狄拉克的电子理论相一致，但却给渴望清楚地解释正电子是如何产生的核物理学家们带来了一系列核物理上亟待解决的问题——通常情况下，正电子是在高能 γ 射线和重粒子甚至是和原子核的相互作用下产生的。布莱克特在这篇文章中对这个问题的处理非常符合一个实验科学家的身份：如何以最佳方式去解释当时断断续续积累起来的关于正电子的实验数据。 [英文](#)

用云室法对宇宙射线的研究引发了正电子的发现^[1]。在和宇宙辐射有关的高能粒子的轨迹中，发现了一些与负电子轨迹完全一致，只是在磁场作用下偏转方向与其相反的轨迹。现在在地球上，我们也能获得低能的正电子，因为已经有研究发现，在物质吸收硬 γ 射线以及在一些核反应发生时都可以产生正电子。因而，在实验室中获得正电子已经是一件很简单的事情了。 [英文](#)

可以根据电离情况计算出正电子的电量和质量。比如，安德森^[2]估计由于快正负电子在磁场中产生相同的偏转轨迹，因而它们之间的电离情况的差别不会大于20%。因为对非常快的粒子来说，电离情况依赖于粒子电量的平方，但是与粒子的质量几乎无关，而正负电子电量之间的差别不可能有10%那么大。另外，对于电量一定的慢粒子，电离情况随粒子质量的变化而变化，所以，相同的电离情况意味着正负电子之间的质量差别应该小于20%。为了得到与正电子性质有关的进一步的信息，我们可以详细地研究产生正电子的最简单的情况，也就是说，研究重元素吸收单色 γ 射线的情况。 [英文](#)

由钷C⁶⁰放射出的 γ 射线经过严格的过滤后将基本达到单色的状态，并带有 2.62×10^6 伏特的能量。安德森和尼德迈耶^[3]，居里和约里奥

[4]，迈特纳和菲利普[5]都发现，当这样的射线照射重元素时，就会产生正电子。[英文](#)

铍受到 α 粒子轰击后的辐射产物被重元素吸收时也可以产生正电子[6]。虽然这种辐射产物很复杂，包括中子和能量大于 5.0×10^6 伏特的 γ 射线，但是居里和约里奥[6]已经通过吸收实验表明，正电子的确主要是由重元素吸收 γ 射线而产生的。[英文](#)

综合居里、约里奥、格林伯格[7]的工作，以及查德威克、布莱克特、奥基亚利尼未发表的结果可以得到下表的数据。此表给出了不同元素在不同放射反应中前向发射的正电子数量与观测到的负电子数量的比值。因为我们并不知道正电子角分布的实际情况，而且可能还应该考虑某个特定的实验装置对实验结果的影响，因此，这些比值只是对正电子产生频率的粗略表示。[英文](#)

吸收 γ 射线所产生的正电子数量

射线源	γ 射线能量	吸收物质		
		铀	铅	铝
镭	$1.0 \times 10^6 \sim 2.2 \times 10^6$ 伏特		3%	
钍 C''	2.62×10^6 伏特		10%	极小
钋和铍	$5 \times 10^6 \sim 6 \times 10^6$ 伏特	大于 40%	40%	5%

[英文](#)

发射出的负电子包含两种成分，一种是带有量子全部能量的光电子，能量为 2.62×10^6 伏特；另一种是前向发射时最高能量为 2.39×10^6 伏特的康普顿电子。如表格所示，正电子的数量随着量子能量和吸收物质原子序数的增加而迅速增加。[英文](#)

如果从上面的数据出发，计算出重原子在吸收一个能量为 5×10^6 伏特的量子后产生正电子的有效面积，则得到的结果远远大于相应原子核的横截面积。这个结果表明，正电子的产生不可能主要是与原子核有关的现象。[英文](#)

对粒子能量的考虑会使以上的观点更令人信服。对于各种不同的吸收物质，在给定的辐射下产生的正电子的最高能量似乎都是大致相同的。如果产生的粒子是由 γ 射线与原子核发生反应所致，那么，不同类

型的原子核所产生的粒子的能量应该是不一样的。

[英文](#)

吸收了辐射能量为 5.0×10^6 伏特和 2.62×10^6 伏特的正电子，其最大能量分别约为 4×10^6 伏特和 1.6×10^6 伏特，也就是说，在各种情况下，正电子的能量都要比量子能量大约少100万伏特。

[英文](#)

如果正电子确实是在原子核外产生的，那么就有以下几个重要结论：

(a) 根据原子理论，既然肯定没有正电子在原子核外长期存在的余地，那么来自那里的正电子必然是在那里产生的，而如果那里产生了正电子，考虑到电荷守恒，那里也必将同时产生一个带有相同电量的负电子。实验上确实观测到了成对的粒子轨迹，这显然可以解释成同时发射出正负电子对，实验有力地证明了以上的结论。

[英文](#)

要产生这样一对正负电子需要消耗的能量为 $(m_1 + m_2)c^2$ 。如果两个粒子的质量都与电子相同，那么这个能量就是 1.01×10^6 伏特，这样，在辐射能量为 2.62×10^6 伏特时，产生的正负电子对的能量就不可能超过 1.61×10^6 伏特。安德森证实了上述的情况。此外，没有形成成对轨迹的单个正电子的最大能量应该也是 1.61×10^6 伏特。查德威克、布莱克特和奥基亚利尼用实验测定了这个能量的最大值，他们得到的初步结果是 $1.58 \pm 0.07 \times 10^6$ 伏特，和理论值非常吻合。

[英文](#)

(b) 正电子应该具有 $\frac{1}{2}$ 的自旋，并遵循费米-狄拉克统计。由于观察到能量在正负电子产生阶段是守恒的，那么可以预见，在该阶段动量和角动量也是守恒的。因为一个量子只能激发角动量改变0或1的变化，所以如果一个量子产生一对粒子，其中一个带有自旋 $\frac{1}{2} \frac{h}{2\pi}$ ，另一个一定具有相同的自旋。即使把可能出现的把原子核自旋的变化也考虑进来，这个论点仍然成立，因为这些自旋的变化应该也是按整数变化的。

[英文](#)

(c) 一个量子和一个原子相互作用产生一对电性相反的电子，这个过程的必然结果是会出现一个逆过程，在这个逆过程中，一个正电子和一个负电子相互作用并与一个原子场作用以产生一个量子的辐射。由于

发生这种情况的条件并不罕见，因而可以预期，在一般密度的物质中，正电子是不可能长期存在的。 [英文](#)

根据实验数据并运用简单的物理原理，我们得到了关于正电子的存在状态及其性质的结论。狄拉克的电子理论预言了具有这些性质的粒子的存在，因而有充分的理由相信他的理论是基本正确的。 [英文](#)

狄拉克成功地构建了电子在势场中运动的波动方程，并保证了方程的相对论不变性。对于氢原子而言，这个新波动方程的解不仅完全解释了谱线的精细结构，还给出了电子本身存在自旋和磁矩的合理解释。

[英文](#)

然而，除了与实验中观测到的正常电子能级相对应的解以外，还有一些解不与任何可观测到的现象相对应。这些解似乎预见到了电子具有负动能的状态，因而无法对应于任何一般意义上的粒子。这些电子态不能被忽略，因为理论上存在这些电子态和对应于正动能的正常态之间的量子跃迁。狄拉克提出，如果假设正常情况下所有的负能态都被占满，并且这些态上的所有电子都不产生外场，那么这个理论上的困难就被排除了。 [英文](#)

从这个观点来看，只有未被占据的负能电子态或“空穴”才能对应于实验上可观测到的粒子。根据理论进一步得出，这些未被占据的负能电子态在外场中表现得就像一些与负电子具有相同质量和自旋，但带有相反电荷的粒子。实验上发现了正电子进而解决了一个重大的理论难题，而在这个理论难题得到解决之后，狄拉克理论可以解释的现象也随之得到了极大的扩展。 [英文](#)

由于分析上的困难，将狄拉克理论应用于某些特殊现象的工作并没有深入开展，但是奥本海默和普莱赛特^[8]已经大致地计算了物质吸收硬 γ 射线时产生带相反电荷的电子对的概率。这些理论上的结果，无论在反应发生的量级上，还是在反应对量子能量和吸收物质原子序数的依赖情况上，都与实验结果大致吻合。 [英文](#)

由理论计算得出：由于正电子的产生，铅和锡作为吸收物质额外多吸收了 2.62×10^6 伏特的辐射能量，这个能量是正常散射情况下所吸收

能量的25%，或是光电反应过程中所吸收能量的15%。这些数据与塔兰特和格雷观测到的实验结果基本一致。因此我们可以得到这样的结论：大部分的反常吸收都有可能归因于正电子的产生。 [英文](#)

我们可以预期，吸收的能量可以以两种方式再次辐射。一是发射出来的一个正电子可能会在与使其产生相逆的过程中消失，也就是说，和一个负电子以及原子核发生相互作用，产生一个能量为100万伏特量级的量子（见上面的结论（c））。二是按照狄拉克的理论，正电子也可以以另一种方式消失，即正电子和一个自由的或处于弱束缚状态的负电子发生相互作用后，两者都消失并放射出两个能量为50万伏特的量子。[†]值得注意的是，由塔兰特和格雷估计的再次辐射的能量主要就是由这两部分所组成，即50万伏特和100万伏特。但是，费米和乌伦贝克^[9]发现，理论上硬成分的辐射能量的强度要远远小于实验上的观测值。

[英文](#)

我们可以把原子吸收硬 γ 射线从而产生带有相反电荷的电子对的过程看作是一个通过“虚”电子来实现的光电吸收过程，这个“虚”电子即原子核附近具有负动能的电子。根据贝克^[10]的理论研究，我们可以认为这些虚电子具有 $2mc^2$ 量级的结合能。贝克还表示，吸收过程中的有效电子数和原子序数的平方成正比，并且每个铅原子中大约有一个虚电子。理论结果还显示，电子对的产生过程发生在与原子核的距离小于 $h/2\pi mc = 3.85 \times 10^{-11}$ cm的范围内，这个范围恰好在K壳层之内。

[英文](#)

居里和约里奥^[11]发现，当铝和硼被 α 粒子轰击时产生正电子，而这些正电子的能量高于伴随其产生的负电子的能量。然而银、锂、石蜡在 α 粒子轰击下没有产生正电子。居里和约里奥认为，正电子是在原子核的裂变过程中产生的，但是似乎是由原子核发射出的 γ 射线内转换而成，而这个过程有可能主要发生在原子核之外。为了用这种方式解释正电子的产生， γ 射线的内转化概率必须接近单位1。[‡]正电子比负电子能量高可以解释为：为了从原子核势场中逃逸，正电子要获得能量，而负电子要损失概率。电子对产生的位置越靠近原子核则最终的动能差异也将越大，因而对于上述的内转换过程这个能量的差异也会大于通常的外部吸收过程，因为前者依赖于球面波，而后者依赖于平面波。 [英文](#)

虽然正电子的最初发现和宇宙辐射有关，但目前还不清楚正电子在这个复杂现象中到底扮演什么样的角色。不过有以下几点是可以肯定的^[12]：(i) 在海平面上发生宇宙射线电离的快粒子中，正负电子大约各占一半。它们的能量从几百万伏特到将近 10^{10} 伏特不等。(ii) 在“簇射”中也得到了相同的正负电子比。因此簇射似乎意味着由初级辐射引发的一次或多次碰撞过程导致了许多对正负电子的产生。狄拉克理论指出，在吸收 γ 射线和高能粒子的过程中产生了单个电子对，这具有重大的意义^[13]，但是到现在为止，这些还不能为形成簇射的多个电子对的产生机制提供线索。(iii) 事实表明，绝大多数入射到地球大气层中的粒子都带有正电荷^[14]。 英文

由于在海平面上极少能探测到质子，那么带正电荷的入射粒子就很有可能是正电子而不是质子。如果事实的确如此，那么跨星系空间的宇宙射线流将主要由正电子构成；既然已经估算出这些辐射粒子的总质量大约是所有恒星和星云质量的 $1/1,000$ ^[15]，那么可以认为，虽然正电子因为寿命短暂而在地球上很少见，但它仍然是整个宇宙的重要组成部分。 英文

(王静 翻译；李军刚 审稿)

* 正电子的质量可以通过以下方程

$$E_{\max} = hv - (m_1 + m_2)c^2$$

并代入 $hv = 2.62 \times 10^6$ 伏特， $E_{\max} = 1.58 \pm 0.07 \times 10^6$ 伏特得到。

我们发现

$$m_2 = (1.04 \pm 0.14)m_1$$

这个结果给出了迄今为止人们对正电子质量的最为精确的估计值。

† 狄拉克计算了这种湮灭的概率，结果表明一个正电子在水中的寿命要小于 10^{-9} 秒，并且其寿命与密度成反比。如果这个预测的过程得到了实验上的证明，那么就可以假定逆过程是有可能存在的，即通过两个

高能量子的碰撞产生一对符号相反的电子。后一个过程后来成为第一例已知的量子“干涉”；可想而知这个过程所具有的重大宇宙学意义。

‡ 奥本海默和普莱塞特（在上述引文中）预测的理论值要小得多。

The Ether-drift Experiment and the Determination of the Absolute Motion of the Earth*

D. C. Miller

The ether-drift experiment was that in which Michelson and Morley in 1892, using an optical interferometer they had constructed in Ohio in the United States, demonstrated that the supposed ether filling all of space did not exist. This paper uses similar equipment to work out what is called the “absolute” movement of the Solar System through space. The use of the term “absolute” pays scant attention to the theory of relativity, but the result does suggest how the Solar System is moving with respect to the surrounding galaxies.

[中文](#)

THE ether-drift experiment first suggested by Maxwell in 1878 and made possible by Michelson’s invention of the interferometer in 1881, though suitable for the detection of the general absolute motion of the Earth, was actually applied for detecting only the known orbital component of the Earth’s motion. For the first time, in 1925 and 1926, I made observations at Mount Wilson of such extent and completeness that they were sufficient for the determination of the absolute motion of the Earth. These observations involved the making of about 200,000 single readings of the position of the interference fringes.

[中文](#)

The ether-drift observable in the interferometer, as is well known, is a second order effect; and the observations correctly define the line in which the absolute motion takes place, but they do not determine whether the motion in this line is positive or negative in direction.

中文

At the Kansas City meeting of the American Association for the Advancement of Science, in December, 1925, before the completion of the Mount Wilson observations, a report was made showing that the experiment gives evidence of a cosmic motion of the solar system, directed towards a northern apex; but the effects of the orbital motion were not found, though it seemed that the observations should have been quite sufficient for this purpose¹. 中文

The studies of the proper motions and of the motions in the line of sight of the stars in our galaxy have shown that the solar system is moving, *with respect to our own cluster*, in the general direction of a northern apex in the constellation Hercules. This apex is near that indicated by the ether-drift observations as just reported, and seemed to be confirmatory evidence of its correctness. Probably it was this that caused the continuation of the analysis of the problem, on the supposition that the absolute motion was to the northward in the indicated line. All possible combinations and adjustments failed to reconcile the computed effects of combined orbital and cosmic motions with the observed facts. 中文

In the autumn of 1932, a re-analysis of the problem was made, based upon the alternative possibility that the motion of the solar system is in the cosmic line previously determined, but is in the opposite direction, being directed southward. This gives wholly consistent results, leading for the first time to a definite quantitative determination of the absolute motion of the solar system, and also to a positive detection of the effect of the motion of the Earth in its orbit.

中文

The absolute motion of the Earth may be presumed to be the resultant of two independent component motions. One of these is the orbital motion around the Sun, which is known both as to magnitude and direction. For the purposes of this study, the velocity of the orbital motion is taken as 30 kilometres per second, and the direction changes continuously through the year, at all times being tangential to the orbit. The second component is the cosmical motion of the Sun and the solar system. Presumably this is constant in both direction and magnitude, but neither the direction nor magnitude is known; the determination of these quantities is the particular object of this experiment. The rotation of the Earth on its axis produces a velocity of less than four tenths of a kilometre per second in the latitude of observation and is negligible so far as the velocity of absolute motion is concerned; but this rotation has an important effect upon the apparent direction of the motion and is an essential factor in the solution of the problem. Since the orbital component is continually changing in direction, the general solution is difficult; but by observing the resultant motion when the Earth is in different parts of its orbit, a solution by trial is practicable. For this purpose it is necessary to determine the *variations* in the magnitude and in the direction of the ether-drift effect throughout a period of twenty-four hours and at three or more epochs of the year. The observations made at Mount Wilson correspond to the epochs April 1, August 1 and September 15, 1925, and February 8, 1926. [中文](#)

The point on the celestial sphere towards which the Earth is moving because of its absolute motion is called the apex of its motion. This point is defined by its right ascension and declination, as is a star, and the formulae of practical astronomy are directly applicable to its determination from the interferometer observations. The theoretical consideration of the determination of the apex of the motion of the Earth has been given in a paper by Prof. J. J. Nassau and Prof. P. M. Morse². [中文](#)

Table I gives the right ascensions and declinations of the apexes of the Earth’s cosmical motion as obtained from the interferometer observations for the four epochs on the presumption of a southward motion, together with the right ascensions and declinations calculated upon the theory of an ether-drift. [中文](#)

Table I. Location of resultant apexes

Epoch	α (Obs.)	α (Calc.)	δ (Obs.)	δ (Calc.)
Feb. 8	6 ^h 0 ^m	5 ^h 40 ^m	-77° 27′	-78° 25′
April 1	3 42	4 0	76 48	77 50
Aug. 1	3 57	4 10	64 47	63 30
Sept. 15	5 5	5 0	62 4	62 15

Apex of cosmic component $\alpha = 4^h 56^m$, $\delta = -70^\circ 33'$

From these resultant apexes are determined four values for the apex of the cosmic component, which is the apex of the motion of the solar system as a whole. This apex has the right ascension 4^h 56^m and the declination 70° 33′ south. [中文](#)

Continuing the astronomical description, having found the elements of the “aberration orbit”, these are used to compute the apparent places of the resultant apexes for the four epochs of observation. On the accompanying chart of the south circumpolar region of the celestial sphere (Fig. 1), the large star indicates the apex of the cosmic motion, and the four circles show the locations of the calculated apexes. These apexes necessarily lie on the closed curve representing the calculated aberration orbit, the centre of which is the apex of the cosmic component of the Earth’s motion. This aberration orbit is the projection of the Earth’s orbit on the celestial sphere, which in this case is approximately a circle. The observed apexes for the four epochs are represented by the small stars. The locations of the pole of the ecliptic and of the star Canopus are also shown. The close agreement between the calculated and observed apparent apexes would seem to be conclusive evidence of the validity of the solution of

the ether-drift observations for the absolute motion of the Earth and also for the effect of the orbital motion of the Earth, which hitherto has not been demonstrated. [中文](#)

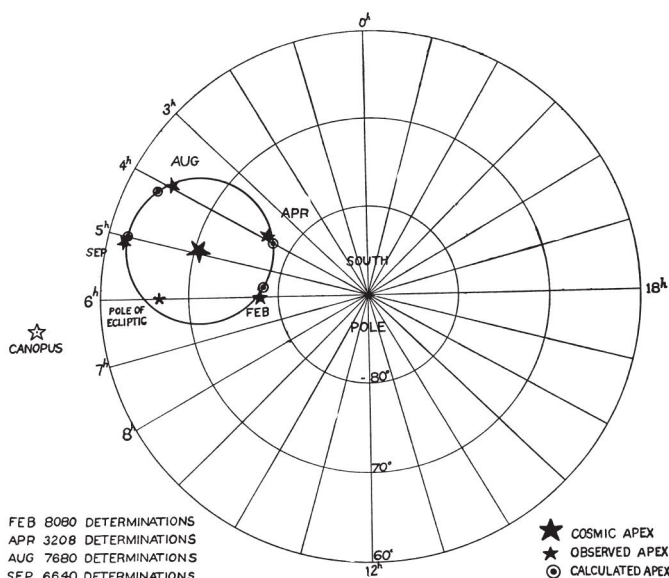


Fig. 1. Observed and calculated apexes of the absolute motion of the solar system. [中文](#)

It may seem surprising that such close agreement between observed and calculated places can be obtained from observations of such minute effects, and effects which are reputed to be of such difficulty and uncertainty. Perhaps an explanation is the fact that the star representing the final result for the February epoch is, in effect, the average of 8,080 single determinations of its location; the star for the August epoch represents 7,680 single determinations, that for September, 6,640, and that for April, 3,208 determinations. [中文](#)

The location of the apex of the solar motion is in the southern constellation Dorado, the Sword-Fish, and is about 20° south of the star Canopus, the second brightest star in the heavens. It is in the midst of the famous Great Magellanic Cloud of stars. The apex is about 7° from the pole of the ecliptic and only 6° from the pole of the invariable plane of the solar system; thus the indicated motion of the

solar system is almost perpendicular to the invariable plane. This suggests that the solar system might be thought of as a dynamic disc which is being pulled through a resisting medium and therefore sets itself perpendicular to the line of motion. 中文

It is presumed that the Earth’s motion in space is projected on to the plane of the interferometer, and the *direction* of this motion is determined by observing the variations produced in the projected component by the rotation of the Earth on its axis and by the revolution around the Sun. Both the magnitude and the direction of the observed effect vary in the manner and in the proportion required by an ether-drift, on the assumption of a stagnant ether which is undisturbed by the motion of the Earth through it. But the observed *magnitude* of the effect has always been less than was to be expected, indicating a reduced velocity of relative motion, as though the ether through which the interferometer is being carried by the Earth’s motion were not absolutely at rest. The orbital velocity of the Earth being known, 30 kilometres per second, the cosmical velocity of the solar system, determined from the proportional variations in the observed effects, is found to be 208 kilometres per second. 中文

Table II gives the observed periodic displacement of the fringe system as the interferometer rotates on its axis, and the corresponding velocity of relative motion of the Earth and ether. 中文

Table II. Displacements and velocities

Epoch	Fringe Shift	Velocity (Obs.)	Velocity (Calc.)
Feb. 8	0.104 <i>l</i>	9.3 km./sec.	195.2 km./sec.
April 1	0.123	10.1	198.2
Aug. 1	0.152	11.2	211.5
Sept. 15	0.110	9.6	207.5

The last column gives the velocity to be expected in the stagnant ether theory on the presumption that the cosmic component and the orbital component are both reduced in the same proportion in the

interferometer. The mean factor of reduction is $k = 0.0514$. The azimuth of the observed effect is subject to a diurnal variation, produced by the rotation of the Earth on its axis. The observed oscillations of the azimuth are in accordance with theory as to magnitude and time of occurrence, but for some unexplained reason, the axis of the oscillations is displaced from the meridian. In order to account for the results here presented, it seems necessary to accept the reality of a modified Lorentz–FitzGerald contraction, or to postulate a viscous or dragged ether as proposed by Stokes. [中文](#)

The results here reported are, notwithstanding a common belief to the contrary, fully in accordance with the original observations of Michelson and Morley of 1887, and with those of Morley and Miller of 1904–5. The history of the ether-drift experiment and a description of the method of using the interferometer, together with a full account of the observations and their reduction, has been published elsewhere³.

[中文](#)

(133, 162-164; 1934)

Dayton C. Miller: Case School of Applied Science, Cleveland, Ohio.

References:

1. *Science*, **63**, 433; 1926. *Nature*, **116**, 49; 1925.
2. *Astrophys. J.*, March, 1927.
3. *Rev. Mod. Phys.*, **5**, 203, July, 1933.

* Paper read before Section A (Mathematical and Physical Sciences) of the British Association meeting at Leicester on September 13, 1933.

以太漂移实验和地球绝对运动的确定*

米勒

迈克尔逊和莫雷于1892年用他们在美国俄亥俄州建造的光学干涉仪进行了以太漂移实验，实验表明原先假设充满整个宇宙的以太其实并不存在。这篇文章利用相似的仪器测量了太阳系在宇宙中的“绝对”运动。使用“绝对”这个术语表明作者没有考虑到相对论，但是实验结果的确表明了太阳系是如何相对于周围星系运动的。 [英文](#)

1878年麦克斯韦首次提出了以太漂移实验，1881年迈克尔逊发明的干涉仪使该实验成为可能。虽然这个实验可以适用于探测地球总体的绝对运动，但实际上它仅在探测人们所熟知的地球运动的轨道分量时被应用过。1925~1926年，我在威尔逊山上进行了首次观测，这次观测无论从范围上还是完备性上都足以用来确定地球的绝对运动。这些观测数据包含大约200,000个单独的干涉条纹位置的读数。 [英文](#)

众所周知，干涉仪中可观察到的以太漂移是一个二阶效应；通过观测可以准确地确定绝对运动的路线，但无法确定沿该路线运动的方向。

[英文](#)

1925年12月，即威尔逊山的观测完成之前，美国科学促进会在堪萨斯城召开了一个会议，会议上的一个报告指出，实验证明，太阳系在宇宙中是朝着一个北向点运动的；尽管这个实验似乎应当足以观测到轨道运动的效应^[1]，但是这一目的并未达到。 [英文](#)

对银河系中恒星的自行和视向运动的研究表明，相对于我们本星系团，太阳系是大致朝着武仙座北向点的方向运动的。这个向点和前述报

告中的以太漂移观测所示出的方向接近，这似乎是证明其正确性的有力证据。也许，这正是导致接下来的研究都假设绝对运动是沿着所示路线向北的原因。然而在这种假定下，所有可能的组合和调整都不能使计算得到的轨道和宇宙运动的联合效应与实际的观测结果相符。 [英文](#)

1932年秋，人们基于另外一种可能性重新对这个问题进行了分析，即太阳系沿着之前确定的宇宙轨道运动，但方向相反，也就是向南运动。这一次得到了完全一致的结果，从而第一次定量地确定了太阳系的绝对运动，同时也首次明确地探测到了地球在其轨道内的运动效应。

[英文](#)

地球的绝对运动可以被看成是两个独立运动分量的和。其中一个绕太阳的轨道运动，其大小和方向都是已知的。在此项研究中，地球轨道运动的速度取为30千米/秒，其方向在一年中连续变化，并总是沿着轨道切线的方向。第二个分量是太阳和太阳系在宇宙中的运动。假设该运动的大小和方向都是恒定的，但均属未知；确定这些量正是这项实验的目的。在进行观测的纬度处，地球绕轴的自转将产生一个小于0.4千米/秒的速度，这相对于地球绝对运动速度而言可以忽略不计；但是地球自转对运动的视方向有着重要的影响，这也是求解此问题时的一个重要因素。由于轨道运动分量在方向上持续变化，所以要得到通解很困难；但是通过观测地球在轨道不同位置的合运动，从而得到实验解还是可行的。为此，必须在一年中选择三个或者更多个不同的时期，确定以太漂移效应的大小和方向在24小时内的变化。这项观测在威尔逊山上进行，其观测的时期分别是：1925年4月1日、8月1日、9月15日以及1926年2月8日。 [英文](#)

地球绝对运动所指向的天球上的那个点被称为地球运动的向点。天球就如同一颗恒星，这个点可由天球上的赤经和赤纬确定，通过干涉仪的观察结果，利用实测天文学的公式可以直接确定这个点的位置。纳索教授和莫尔斯教授的文章已经对确定地球运动的向点给出了理论思考 [2]。 [英文](#)

表1给出了假定太阳系是在向南运动的情况下，利用干涉仪的观测结果得到的四个时期地球在宇宙中运动相应向点的赤经和赤纬，以及用

以太漂移理论计算得到的相应值。[英文](#)

表1．地球在宇宙中合运动的向点位置

时期	赤经（观测值）	赤经（计算值）	赤纬（观测值）	赤纬（计算值）
2月8日	6 小时 0 分	5 小时 40 分	-77° 27′	-78° 25′
4月1日	3 42	4 0	76 48	77 50
8月1日	3 57	4 10	64 47	63 30
9月15日	5 5	5 0	62 4	62 15

宇宙分量的向点 赤经 = 4小时56分，赤纬 = -70°33′

由上表中四个合运动的向点可以确定宇宙分量的向点，它也是太阳系作为一个整体运动的向点。这个向点的位置是赤经4小时56分，赤纬-70°33′。[英文](#)

让我们继续天文学的描述，在得出“光行差轨道”的根素后，即可以用其计算出四个观测时期合运动的向点的视位置。附图是天球南拱极区（图1），图中大星号表示宇宙运动的向点，四个圆圈表示计算得到的向点位置。这些向点必须落在计算得到的光行差轨道的闭合曲线上，光行差轨道的中心即为地球运动宇宙分量的向点。此光行差轨道是地球轨道在天球上的投影，在这种情况下近似为圆。在四个时期观测到的向点在图中以小星号表示。图中还标出了黄极和老人星的位置。计算和观察得到的视向点的高度吻合似乎有力地证明了用以太漂移观测来求解地球绝对运动以及地球轨道运动效应的正确性，而对于后者迄今为止尚未得到实验证明。[英文](#)

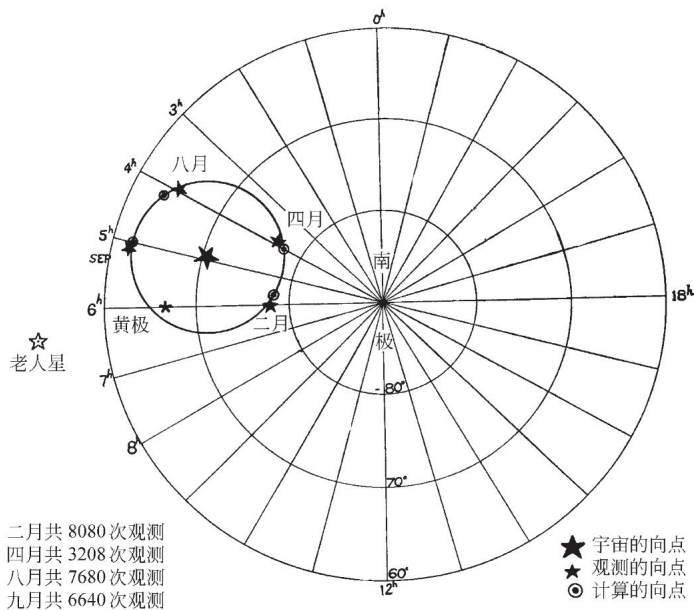


图1．太阳系绝对运动顶点的观测位置和计算位置 [英文](#)

令人惊奇的是，虽然以太漂移这种微弱的效应被公认为是难于观测且其结果会有很高的不确定性，但最后却得到了计算值和观察值如此高度一致的结果。也许，我们可以这样解释：这些观察结果实际上是由大量独立的位置测量平均得出的，二月有8,080次单次测定，八月有7,680次，九月有6,640次，而四月有3,208次。 [英文](#)

太阳运动的向点位于南天的剑鱼座内，处在天空中第二亮的老人星以南约20°处，著名的大麦哲伦星云的中间。该向点偏离黄极7°左右，而仅偏离太阳系的不变平面的6°，因此太阳系的运动几乎是垂直于其不变平面的。这表明，太阳系可以被看作是一个动力盘，这个圆盘被牵引着穿过某种阻尼介质，从而使其与运动路线垂直。 [英文](#)

我们通常假设地球在宇宙中的运动被投影到干涉仪的平面上，通过观测由于地球的自转和绕太阳的公转所引起的这一投影分量的变化可以确定该运动的方向。观测到的效应的大小和方向均和假设以太静止时，即以太不被运动的地球所扰动时所预期的变化方式和比例相符。但是，观测到的效应的值总比预期的小，这表明相对运动速度的减小，这似乎表明载着干涉仪的地球所穿过的以太并不是绝对静止的。已知地球的轨道速度为30千米/秒，而根据观测到的效应成比例变化而确定的太阳系

的宇宙速度为208千米/秒。[英文](#)

表2给出了干涉仪绕其轴旋转时观测到的条纹系统的周期性位移，以及相应的地球和以太的相对运动速度。[英文](#)

表2．位移和速度

时期	条纹位移	速度（观测值）	速度（计算值）
2 月 8 日	0.104 <i>l</i>	9.3 千米 / 秒	195.2 千米 / 秒
4 月 1 日	0.123	10.1	198.2
8 月 1 日	0.152	11.2	211.5
9 月 15 日	0.110	9.6	207.5

假设干涉仪所测得的宇宙分量和轨道分量都以相同的比例减小，最后一列给出的是在静止以太理论下的预期速度。平均减缩因子 $k=0.0514$ 。观测到的效应的方位角由于地球的绕轴自转存在周日变化。观测到的方位角振荡在大小和时间上与理论结果一致，但是由于一些未知原因，振荡轴偏离了子午线。为了解释这里给出的结果，似乎必须要接受修正后的洛伦兹-斐兹杰惹收缩理论，或者像斯托克斯所提出的那样，假设以太有黏性或具有拖曳效应。[英文](#)

尽管这里给出的结果与普遍的观念相反，但却与1887年迈克尔逊、莫雷所进行的原始观测以及1904 ~ 1905年莫雷、米勒所进行的实验观测完全一致。另外，我们已经在其他刊物^[3]上发表了相关的内容，包括以太漂移实验的发展、利用干涉仪进行实验的相关方法，以及进行观测及其归算过程的完整说明等。[英文](#)

（王静 孙惠南 翻译；邓祖淦 审稿）

* 本论文发表于1933年9月13日在莱切斯特举行的英国科学促进会会议A分会场（数学与物理科学）。

Artificial Production of a New Kind of Radio-element

F. Joliot and I. Curie

Scientists were still exploring the kinds of nuclear transmutations that could be induced by bombarding stable elements with particles such as alpha particles. Here Irène Curie and Frédéric Joliot report the formation of new, unstable isotopes of nitrogen, silicon and phosphorus made by alpha-irradiation of aluminium, boron and magnesium. The new “radio-elements” are evident from their decay over periods of several minutes, with emission of positrons. Uniquely, the two French scientists use chemical methods to separate the new isotopes and thereby identify their chemical nature. Short-lived positron-emitting isotopes, including the nitrogen-13 reported here, are now used in the medical imaging technique of positron emission tomography. (Note that the third paragraph seems to mistakenly mention “beryllium” in place of “boron”.) [中文](#)

SOME months ago we discovered that certain light elements emit positrons under the action of α -particles¹. Our latest experiments have shown a very striking fact: when an aluminium foil is irradiated on a polonium preparation, the emission of positrons does not cease immediately, when the active preparation is removed. The foil remains radioactive and the emission of radiation decays exponentially as for an ordinary radio-element. We observed the same

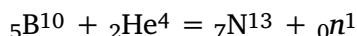
phenomenon with boron and magnesium². The half life period of the activity is 14 min. for boron, 2 min. 30 sec. for magnesium, 3 min. 15 sec. for aluminium. [中文](#)

We have observed no similar effect with hydrogen, lithium, beryllium, carbon, nitrogen, oxygen, fluorine, sodium, silicon, or phosphorus. Perhaps in some cases the life period is too short for easy observation.

[中文](#)

The transmutation of beryllium, magnesium, and aluminium α -particles has given birth to new radio-elements emitting positrons. These radio-elements may be regarded as a known nucleus formed in a particular state of excitation; but it is much more probable that they are unknown isotopes which are always unstable. [中文](#)

For example, we propose for boron the following nuclear reaction:



${}_7\text{N}^{13}$ being the radioactive nucleus that disintegrates with emission of positrons, giving a stable nucleus ${}_6\text{C}^{13}$. In the case of aluminium and magnesium, the radioactive nuclei would be ${}_{15}\text{P}^{30}$ and ${}_{14}\text{Si}^{27}$ respectively. [中文](#)

The positrons of aluminium seem to form a continuous spectrum similar to the β -ray spectrum. The maximum energy is about 3×10^6 e.v. As in the case of the continuous spectrum of β -rays, it will be perhaps necessary to admit the simultaneous emission of a neutrino (or of an antineutrino of Louis de Broglie) in order to satisfy the principle of the conservation of energy and of the conservation of the spin in the transmutation. [中文](#)

The transmutations that give birth to the new radio-elements are produced in the proportion of 10^{-7} or 10^{-6} of the number of α -particles, as for other transmutations. With a strong polonium

preparation of 100 millicuries, one gets only about 100,000 atoms of the radioactive elements. Yet it is possible to determine their chemical properties, detecting their radiation with a counter or an ionisation chamber. Of course, the chemical reactions must be completed in a few minutes, before the activity has disappeared. [中文](#)

We have irradiated the compound boron nitride (BN). By heating boron nitride with caustic soda, gaseous ammonia is produced. The activity separates from the boron and is carried away with the ammonia. This agrees very well with the hypothesis that the radioactive nucleus is in this case an isotope of nitrogen. [中文](#)

When irradiated aluminium is dissolved in hydrochloric acid, the activity is carried away with the hydrogen in the gaseous state, and can be collected in a tube. The chemical reaction must be the formation of phosphine (PH_3) or silicon hydride (SiH_4). The precipitation of the activity with zirconium phosphate in acid solution seems to indicate that the radio-element is an isotope of phosphorus.

[中文](#)

These experiments give the first chemical proof of artificial transmutation, and also the proof of the capture of the α -particle in these reactions³. [中文](#)

We propose for the new radio-elements formed by transmutation of boron, magnesium and aluminium, the names *radionitrogen*, *radiosilicon*, *radiophosphorus*. [中文](#)

These elements and similar ones may possibly be formed in different nuclear reactions with other bombarding particles: protons, deuterons, neutrons. For example, ${}^7\text{N}^{13}$ could perhaps be formed by the capture of a deuteron in ${}^6\text{C}^{12}$, followed by the emission of a neutron. [中文](#)

(133, 201-202; 1934)

References:

1. Irène Curie and F. Joliot, *J. Phys. et. Rad.*, **4**, 494; 1933.
2. Irène Curie and F. Joliot, *C.R.*, **198**; 1934.
3. Irène Curie et F. Joliot, *C.R.*, meeting of Feb. 29, 1934.

一种新放射性元素的人工制造

约里奥，居里

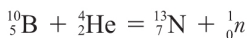
科学家们仍旧在探寻粒子（比如 α 粒子）轰击稳定元素所导致的核嬗变的种类。这篇文章中伊雷娜·居里和弗雷德里克·约里奥报道了有关通过 α 粒子照射铝、硼和镁分别产生了氮、硅和磷的新的不稳定同位素的信息。从它们在数分钟内放出正电子的衰变来看，新“放射性元素”的存在是证据确凿的。特别的是，这两位法国科学家使用化学方法分离出了这些新的同位素，从而鉴定了它们的化学性质。短寿命的放射正电子的同位素，包括本文中所报道的氮-13，现在被用在正电子发射层析的医学成像技术中。（注意文中第三段似乎将“硼”错写成了“铍”。） [英文](#)

几个月之前，我们发现某些轻元素在 α 粒子的作用下会放出正电子^[1]。我们最近的实验得到了一个令人十分惊喜的结果：以钋样品所产生的辐射照射铝箔，当移开放射性的钋样品时，正电子的发射不会立即停止。铝箔仍然保持着放射性，辐射就像普通的放射性元素一样以指数形式衰减。对于硼和镁，我们也观察到了同样的现象^[2]。放射性活度的半衰期分别是：硼14分钟、镁2分30秒、铝3分15秒。 [英文](#)

我们在氢、锂、铍、碳、氮、氧、氟、钠、硅和磷等元素中都没有观测到类似的效应。也许在某些情况下由于这一效应寿命过短，所以通过简易的观测无法观测到。 [英文](#)

在 α 粒子作用下，铍、镁和铝元素嬗变产生了新的发射正电子的放射性元素。这些放射性元素可以视为是处于特定的激发态上的一个已知的核，不过它们是未知同位素的可能性更大，而通常这些同位素都是不稳定的。 [英文](#)

例如，我们认为硼发生了下面的核反应：



其中 ${}^{13}_7\text{N}$ 是一个放射性核，蜕变时放出正电子，最终得到一个稳定的核 ${}^{13}_6\text{C}$ 。对于铝和镁来说，所得到的放射性核分别是 ${}^{30}_{15}\text{P}$ 和 ${}^{27}_{12}\text{Mg}$ 。[英文](#)

铝放出的正电子似乎构成一个类似于 β 射线谱的连续谱，其最大能量约为 $3 \times 10^6 \text{eV}$ 。就 β 射线的连续谱来说，为了在嬗变中满足能量守恒与自旋守恒的原则，允许同时放出一个中微子（或者一个路易斯-德布罗意的反中微子）似乎是必要的。[英文](#)

至于其他的嬗变情况，产生新放射性元素的嬗变正比于 α 粒子数的 10^{-7} 或 10^{-6} 。使用放射性强度达100毫居的钋样品，我们也只能得到大约100,000个放射性元素的原子。不过，使用计数器或者电离室来探测它们的辐射，就可以确定它们的化学性质。当然，前提是它们在放射性活度消失之前的几分钟内完成化学反应。[英文](#)

我们已经照射了化合物氮化硼（BN）。使用苛性钠溶液来加热氮化硼，可以产生气态的氨。实验结果表明，放射活性与硼元素分离并转移到氨中了。这个结果与此种情况中放射性核是氮的一个同位素这一假设吻合得很好。[英文](#)

将被照射的铝溶解于盐酸中，放射活性会被氢转移到气态，且可以被收集在试管中。该化学反应必定形成了磷化氢（ PH_3 ）或者四氢化硅（ SiH_4 ）。而在酸性溶液中，放射活性与磷酸锆一起沉淀下来，这似乎意味着放射性元素是磷的一个同位素。[英文](#)

这些实验给出了人工嬗变的第一个化学证据，同时也给出了在上述的反应中 α 粒子被俘获的证据^[3]。[英文](#)

我们提议将以硼、镁和铝嬗变形成的新的放射性元素命名为放射性氮、放射性硅和放射性磷。[英文](#)

在使用其他轰击粒子，如质子、氘、中子引起的一些核反应中，也有可能生成这些元素或者类似的其他元素。例如， ${}^{12}_6\text{C}$ 俘获一个氘后，

释放出一个中子，就有可能会形成 ${}^{13}_7\text{N}$ 。

英文

(王耀杨 翻译；张焕乔 审稿)

A Velocity-modulation Television System

In the mid 1930s, many groups were developing technology for transmitting visual images over long distances. Here *Nature* reports on a recent advance. Most approaches produced an image by scanning a cathode ray rapidly over a fluorescent screen. Modulations of the ray intensity translate into lighter or darker parts of the image. But improved images could be obtained by modulating the velocity of the ray, rather than its amplitude, with the screen being naturally darker where the ray passes more quickly. The article notes that engineers had recently reported on advances in such a system, and demonstrated in laboratory tests that intensity modulation could be used in addition to improve the contrast of the images. [中文](#)

MANY of the investigators who are seeking at the present time to develop a practical system of television make use of the cathode ray oscillograph tube in one form or another, since the electron beam in such a tube provides an easily controlled means of scanning the picture to be transmitted. At the receiving end, the cathode ray tube is employed to build-up the received picture by varying the intensity of the beam in accordance with the light and dark portions of the picture. The ordinary type of cathode ray tube, however, gives only a small range of intensity control without the accompaniment of loss of focus of the spot on the fluorescent screen, and special electrode systems have to be arranged to obtain good intensity modulation in

this manner. As an alternative to this method, the intensity of the cathode ray beam may be kept constant but its transverse velocity may be varied as it moves over the picture, the beam being speeded up over the dark portions of the picture and slowed down over the light portions. The corresponding motion of the cathode ray beam at the receiving end thus gives varying illumination according to the speed of travel of the spot on the fluorescent screen, and with the aid of the phenomenon of persistence of vision, a true impression of the shades and contrasts in the picture received is obtained. [中文](#)

The conception of this velocity-modulation principle, or variable-speed cathode ray television, dates back to 1911, when it was described in a British patent by B. Rosing. Since that date the principle appears to have fallen into oblivion until it was revived in Germany by R. Thun in 1929. The first practical realisation of the method was achieved by M. von Ardenne in 1931 and reference was made to this work in *Nature* of October 7 last (p.573). [中文](#)

During the development of cathode ray oscillograph tubes for general scientific and technical purposes, the staff of Messrs. A. C. Cossor Ltd. realised the possibilities of the above system of television, and an account of the development work carried out during the past eighteen months was presented in a paper entitled "A Velocity-Modulation Television System", read before the Wireless Section of the Institution of Electrical Engineers by Messrs. L. H. Bedford and O. S. Puckle on February 7. [中文](#)

Consideration of the basic principles outlined above shows that it is impossible to realise a velocity-modulated picture from a uniformly scanned object; the scanning at the transmitter must also be of the variable-speed or velocity-modulated type, and must therefore be carried out by a cathode ray. It follows that a cathode ray oscillograph must serve as the source of light at the transmitting end, and, with oscillographs of the ordinary low-voltage type, the conditions of

scanning-light economy will restrict the picture subject matter to cinematograph film material. This, however, is not considered to be a disadvantage of the method; many of the television systems being developed at the present time make use of a film as an intermediary, and processes are being devised in which the interval between the photography of the subject and the projection of the picture through the transmitter is reduced to the bare minimum. [中文](#)

The transmitting arrangements described by Messrs. Bedford and Puckle comprise the projection of light from the fluorescent screen of the oscillograph through the film picture on to a photoelectric cell. The output of the photo-cell amplifier operates, through a screen-grid valve and a thyatron, an electrical time-base circuit which supplies the potential difference to one pair of the deflecting plates of the oscillograph. The light from the cathode ray tube is thus swept in a straight line across the picture with a velocity which varies according to its transparency at different points. At the end of each scanning line, the discharge of the thyatron provides a “fly-back” action to the spot sufficiently rapid to be invisible. Simultaneously with this operation, a second valve and thyatron circuit provides a traversing time-base potential difference to the second pair of deflecting plates of the oscillograph tube. By this means the scanning line is traversed across the picture in successive steps. [中文](#)

From this description it will be realised that an image of the picture being transmitted is built up on the fluorescent screen of the cathode ray oscillograph, and this is found to be a useful feature of the system for monitoring purposes. Furthermore, for the reproduction of the image on the screen of another oscillograph tube at a distant receiving station, it is merely necessary to transmit to the second tube the voltages being applied to the two pairs of deflecting plates of the first tube. If these voltages are sent through two separate channels, the received picture is automatically synchronised with that at the

transmitting end. 中文

The authors of the paper referred to above have modified this arrangement to some extent, however, to enable all the intelligence to be sent along a single channel. Using a picture frequency of 25 per second with a detail corresponding to 120 or 160 scanning lines, the transmitted signals require a frequency band of the order of 240 kilocycles per second; and special amplifiers have been developed to give uniform amplification over this range. The size of the picture received depends upon the deflector voltages which may be applied to the oscillograph electrodes, and it is anticipated that future design and manufacture will enable a suitable receiver tube with a 9-inch screen to be produced. Among the advantages of the method described above over that employing intensity-modulation are the increased picture brightness for a given receiving oscillograph and the concentration of detail in the light portions of the picture. 中文

Although Messrs. Bedford and Puckle's experiments have so far been limited to transmission over wire lines, no particular difficulty is anticipated in applying the necessary signals to radio transmission, at least on the ultra-short wave-length of a few metres where such a large frequency band as 240 kc./sec. may be permitted. At the reading of the paper, a cinematograph film was shown illustrating typical pictures received in a laboratory test of the whole system. Among the features brought out in this demonstration was the fact that, when required to obtain a better contrast ratio in the received picture, intensity modulation may be superimposed with advantage upon the velocity-modulation signals, and means of achieving this very satisfactory combination are being investigated. 中文

(133, 263; 1934)

一个基于速度调制的电视系统

20世纪30年代中期，许多研究组都在发展远距离传输可视图像的技术。《自然》的这篇文章介绍了当时的最新进展。大多数技术是通过使用阴极射线快速地扫描荧光屏来产生图像的。调制阴极射线的强度可以反映出图像的亮区和暗区。但是，相对于调制振幅而言，通过调制阴极射线的速度可以得到更加清晰的图像，当射线扫描速度较快时，扫过的区域会自然的较暗。这篇文章介绍了工程师们最近报道的这类系统的进展，同时也指出了在实验室测试中还可以用强度调制来增强图像的对比度。 [英文](#)

目前，许多致力于开发实用电视系统的研究者都在使用各种形式的阴极射线示波管，因为这种示波管中的电子束提供了一种很容易控制的方法来对将要传输的图片进行扫描。在接收端，阴极射线管根据原始图片的明暗区域相应地改变电子束的强度，以实现接收图片的构建。然而，如果不考虑在荧光屏上聚焦点的发散作用，那么一般的阴极射线管能控制电子束的强度范围是很小的，要用这种方式，就必须使用特殊的电极系统才能获得良好的强度调制效果。作为这种方式的一个替代方案，可以保持阴极射线束的强度不变，而使其横向速度在扫过图片时发生变化：通过图片的暗区时，速度加快；通过明区时，速度变慢。于是，根据荧光屏上点的运动速度，接收端的阴极射线束的相应运动就会给出不同的照射强度，借助于视觉暂留现象，人们就能获得对于接收到的图片的明暗区域与对比度的真实现象。 [英文](#)

这种速度调制或者变速的阴极射线电视的概念可以追溯到1911年，当时有一个名为罗辛的人在他的英国专利中提到过。之后这个理论概念就被人们遗忘了，直到1929年德国的图恩再次提起。这一理论的第一次实用化是在1931年由冯·阿登完成的，与此相关的参考文献发表在去年10月7日的《自然》上（第573页）。 [英文](#)

在以一般科学和技术为目的的阴极射线示波管的发展过程中，科索尔有限公司的员工们认识到了上述电视系统的可行性，并且将之前在18个月中完成的大量深入的研究工作都写在了一篇名为《一个基于速度调制的电视系统》的文章里，这篇文章于2月7日由该公司的贝德福德和帕克尔在电气工程师学会无线电分会上进行了宣读。 [英文](#)

根据上面概括的基本原理可以看出，对物体进行匀速扫描是不可能得到速度调制的图片的；在发射端的扫描也一定是速度变化型或是速度可调型的，因此一定也要通过阴极射线来实现。在发射端，阴极射线示波器充当了光源的角色，当使用普通低压型的示波器时，这种扫描光较弱的情况会使扫描图片的材料受到限制，只能使用电影胶片。然而，并不能认为这是此方式的缺点，因为目前正在发展的许多电视系统都把胶片当成一种媒介，过程是这样设计的：将实际物体的相片和通过发射端的相片投影之间的距离减小到几乎为零。 [英文](#)

贝德福德和帕克尔描述的传输设置是将来自示波器的荧光屏的光通过胶片图像投影到光电管上。光电管放大器的输出通过一个屏栅阀和一个闸流管来控制一个电子时基电路，它为示波器的一对偏转片施加电位差。于是，从阴极射线管出来的射线以一条直线扫过图片，根据图片不同位置透光率的不同，扫过的速度也不一样。在每一条扫描线的末端，闸流管的放电产生一个“回扫”的动作使之回到原点，而且速度极快以至于肉眼难以观察到。在进行这个操作的同时，第二个屏栅阀和闸流管电路也对示波管的第二对偏转片施加一个时基的电位差。通过这种方式，扫描线就一条一条地覆盖了整幅图片。 [英文](#)

从上面的描述中可以看出，在阴极射线管的荧光屏上产生了待传输图片的图像，而且这被认为是一个对监视很有用的特点。此外，为了在更远处的接收端的另一个阴极射线管的荧光屏上再现图像，我们只需要将施加在第一个射线管的两对偏转片上的电压传送到第二个射线管中就可以了。如果这两路电压通过不同的通道传输，那么接收的图片就会自动地与发射端的图片进行同步。 [英文](#)

但是，文章的作者们在谈及上面的问题时，对这种设置进行了某种程度的修改，使所有的信息都通过一个信道进行传输。如果使用的图片

频率为每秒25张，每幅图120或160条扫描线，那么传输信号需要的频带的数量级就为每秒240千周；并且他们发展出了一些专用的放大器以保证在这个范围内对信号进行均匀放大。接收图片的大小取决于施加在示波器电极上的偏转电压的大小，而且可以预见到，未来的设计和制造技术将会生产出具有9英寸屏幕的接收管。上述方法相对于强度调节的优点包括：对于给定的接收示波管而言，接收到的图片的亮度会提高，图片亮区的清晰度也会提高。 [英文](#)

虽然到现在为止，在贝德福德和帕克尔的实验中仍只限于用金属线进行传输，但是可以预见到利用无线电传输所需的信号时不会出现其他特殊的困难，至少在波长为几米的超短波长的范围内，频带达到每秒240千周是可以实现的。在读这篇文章的时候，我们已经在整个系统的实验室测试中使用电影胶片得到了典型的图片。从实验中呈现出来的特征可以看出：当接收的图片要求较高的对比度时，强度调制要优于速度调制，而将这两者完美结合还需要进一步探讨。 [英文](#)

（刘东亮 翻译；赵见高 审稿）

The Positron*

C. D. Anderson

In September 1932, Carl Anderson had announced the observation of the positron, a positively charged particle having the same mass as the electron. Here he reviews the discovery and what has been learned since that time. The definitive observation had been made possible, he notes, by having cosmic rays impinge upon a lead target and observing tracks in a cloud chamber held in a high magnetic field. In April 1933, other physicists had shown that a gamma ray in the strong field of a nucleus can create electron-positron pairs. Anderson reviews these experiments in some detail, and notes that the inverse process—the annihilation of an electron and a positron, producing gamma radiation—should also be important, although it had not yet been observed.

[中文](#)

THE existence of free positive electrons or positrons was first reported by me in September 1932¹, from cosmic ray experiments carried out at the California Institute of Technology. In the original paper, all possible alternative interpretations of the effects there presented were discussed in detail, and it was shown that only by calling upon the existence of free positive electrons could those effects be logically interpreted. [中文](#)

As a part of Prof. R. A. Millikan's programme of cosmic ray research, in particular to make energy measurements of the cosmic ray particles

by the use of a vertical cloud chamber in a very powerful horizontal magnetic field, photographs were first taken in August 1931 in such an apparatus involving the maintenance of a field of strength up to 20,000 gauss over a space measuring 17 cm. $\times$ 17 cm. $\times$ 3 cm. As reported in lectures in Paris and Cambridge, England, in November 1931 and published in March 1932 by Millikan and myself², this work brought to light for the first time the fact that nuclear effects are of primary importance in the absorption of cosmic rays, as demonstrated by the frequent occurrence of associated tracks or showers containing particles of positive charge as well as those of negative charge. 中文

Through the insertion in May 1932 of a lead plate across the centre of the cloud chamber, it was possible to show definitely in several cases that the mass of these particles of positive charge could not possibly be as great as that of the proton. The direction of motion of the particles was given in two ways: first, by allowing them to pass through the lead plate and suffer a loss in energy, and secondly, by the observation in several instances of two or more tracks all originating at one small region in the material surrounding the chamber. For a given curvature of track, the specific ionisation showed that the mass was small compared with the proton mass, but even more definite evidence was gained from an observation of the range of the particles. The observed ranges were several times, in some instances more than ten times, greater than the possible ranges of proton tracks of the same curvature. 中文

These considerations were the basis of the report announcing the existence of the free positive electron or positron published in September 1932. Within the next five months a large number of confirmatory photographs revealing unambiguously the existence of positrons was taken, and a second report was published in March 1933³ in which fifteen of these photographs were discussed. The

specific ionisation exhibited by the positron tracks on these photographs showed that the magnitude of charge of the positron could not differ by as much as a factor of two from that of the free negative electron, and it was, therefore, concluded, unless one admits fractional values of the elementary unit of charge, that the free positive and negative electrons were exactly alike in magnitude of charge. This fact, together with the curvatures measured in the magnetic field of a positron before and after it penetrated a plate of lead, fixed its mass as not greater than twenty times that of the free negative electron. [中文](#)

Since then⁴, an observation of a collision between a moving positron and a free negative electron in the gas of the chamber revealed, on the basis of the conservation laws, that its mass was equal to that of the free negative electron with an error of not more than 30 percent. More recent measurements¹⁵ of the specific ionisation of the positives and negatives for both high and low speed particles, by actual ion-counts on the tracks in the magnetic field, showed the specific ionisation of the positives and the negatives to be equal to within 20 percent. This fixes the limits of difference between the positives and negatives with regard to their charges and masses at 10 percent and 20 percent respectively. Further details of the history of this discovery were presented at the American Association for the Advancement of Science meeting in Chicago in June 1933⁴. [中文](#)

In March 1933 confirmatory evidence for the existence of positrons was presented by Blackett and Occhialini⁵, based on similar experiments with a vertical cloud chamber operating in a magnetic field of 3,000 gauss and actuated by the responses of Geiger-Müller counters. In April 1933 Chadwick, Blackett and Occhialini⁶, Curie and Joliot⁷, and Meitner and Philipp⁸ reported that the bombardment of beryllium by α -particles can produce radiation which results in the production of positrons, though in these experiments it was not

possible definitely to identify the nature of the radiation producing the positrons. By absorption experiments, however, Curie and Joliot showed that the yield of positrons decreased approximately as was to be expected if the γ -ray rather than the neutron component of the radiation were responsible for their production. [中文](#)

The first experiments proving directly that a γ -ray photon impinging upon a nucleus gives rise to positrons were carried out at the Norman Bridge Laboratory, using the γ -rays from thorium C'', and reported in April 1933⁹. In this paper the fact that free electrons of both positive and negative sign are produced simultaneously by the impact of a single γ -ray photon, an observation of considerable theoretical import, was first presented. Preliminary results of energy measurements were given in June 1933 by Neddermeyer and myself¹⁰. Curie and Joliot¹¹ in May 1933, and Meitner and Philipp¹² in June 1933, all of whom used γ -rays from thorium C'', also reported the detection of positrons from the same source. Curie and Joliot¹³ have also shown that positrons are produced directly in the disintegration of aluminum and boron by α -particle bombardment. The positrons in the case of aluminum cannot here be produced by the internal conversion of a γ -ray photon unless the probability of such internal conversion is vastly greater than that to be expected on theoretical grounds¹⁴. Rather do these experiments indicate that an elementary positive charge is actually removed from the disintegrating nucleus and appears as a positron. [中文](#)

The foregoing furnishes in brief a historical survey of the early experimental work on positrons and their production. [中文](#)

A detailed study of the energy distribution and frequency of production of free positive and negative electron pairs by filtered thorium C'' γ -rays is of particular value because of the relative simplicity of these effects as compared with those appearing in the cosmic ray range of energies. [中文](#)

γ -ray Effects

A discussion will now be given of experimental evidence as it bears on the theory suggested by Blackett and Occhialini on the basis of the Dirac electron theory, which postulates the creation of a free positive-negative electron pair out of the absorption of a photon impinging upon a nucleus. The nucleus itself in this picture undergoes no disintegration, but plays merely the rôle of a catalytic agent. This discussion will be given in the light of (1) new statistical studies by Neddermeyer and myself on the thorium C" γ -ray effects, and (2) new experiments on cosmic ray showers by Millikan, Neddermeyer, Pickering and myself. [中文](#)

The work of Curie and Joliot, and of Chadwick, Blackett and Occhialini on the radiation from thorium and that excited in beryllium by α -particle bombardment, together with our own work on the cosmic radiation¹⁵, has shown that the absorption process which gives rise to positrons becomes increasingly important with high energy radiations and heavy absorbing materials. Further, we have made a statistical study based on a total of more than 2,500 tracks of single electrons, both positive and negative, and positive-negative pairs ejected from plates of lead, aluminum and carbon by γ -rays from radiothorium filtered through 2.5 cm. of lead (in some cases with unfiltered rays for comparison) to determine the frequency of occurrence of pairs and single positrons, and their energy distribution for absorbing materials of different atomic numbers. The ejection of the particles was observed from lead plates of 0.25 mm. thickness, aluminum plates of 0.5 mm. thickness and a graphite plate of 1.4 cm. thickness (used also for cosmic ray studies). The magnetic field was here adjusted to 825 gauss. [中文](#)

We will consider first of all the energies. Both the single positives and the pairs (the sum of the energies of the positive and negative components being taken) ejected from the lead plates showed a

maximum energy of about 1.6 *MV* (*MV* = millions of electron-volts), 80 percent of the single positrons having an energy less than 0.8 *MV*. For the case of the unfiltered γ -rays, the positrons and the pairs, though occurring in relatively fewer numbers compared with those ejected by the filtered rays, showed also a maximum energy of 1.6 *MV*. Further, in the case of the positives and pairs ejected from the plates of aluminum, the maximum energy was about 1.6 *MV*. [中文](#)

The maximum energy of the single negative electrons in all cases was about 2.5 *MV*. Since the errors in the energy measurements may be as high as 15 percent, this is in good agreement with the highest energy to be expected for extra-nuclear electrons resulting from Compton encounters or photoelectric absorption of the 2.65 *MV* photons. [中文](#)

A maximum energy of 1.6 *MV* for the positives and the pairs, both from the lead and the aluminum, is in good accord with that to be expected on the Dirac picture if 1 *MV* is allowed for the energy required to create a pair of electrons. There occurred, however, one pair the total energy of which was 2.9 *MV*; it is conceivable, though not likely, that it may have been produced by cosmic rays, or again it may represent the rebound of an electron against the under surface of the lead plate. [中文](#)

Of equal importance with the distribution in energy is the distribution in number of single positive electrons and pairs as compared with the single negative electrons. Out of a total of 1,542 electrons ejected from the 0.25 mm. lead plate by γ -rays from radiothorium filtered through 2.5 cm. of lead, there were 1,387 single negatives, 96 single positives and 59 pairs. From an aluminum plate 0.5 mm. thick and ejected by the same radiation there were, out of a total of 943 electron tracks, 916 single negatives, 20 single positives and 7 pairs. [中文](#)

The negatives may be assumed to have arisen in general from

Compton and photoelectric encounters with extra-nuclear electrons in the lead or aluminum. But the single positives and the pairs must all, of course, correspond to nuclear encounters. If we assume that on the average an equal number of positives and negatives results from nuclear impacts, we can calculate the ratio of the nuclear to extra-nuclear absorption. This amounts to about 20 percent for lead and about 50 percent for aluminum. These values are in reasonably good agreement with those obtained by Chao¹⁶, Meitner¹⁷ and Gray and Tarrant¹⁸ by entirely different methods in the matter of the excess absorption shown by lead over that shown by aluminum and also in the general relation of nuclear to extra-nuclear absorption in both metals. [中文](#)

That the nuclear absorption in carbon is very small for the thorium C'' γ -rays is shown by the fact that, as compared with 415 negatives, there appeared only 2 pairs and 6 single positives. [中文](#)

On the whole, the energy relations of the positives and pairs, from both the aluminum and the lead, appear to be quite consistent with the pair-creation hypothesis, as are also the approximate values of the excess absorption in lead and aluminum calculated on this assumption. [中文](#)

The ratio of the observed numbers of single positives compared with the pairs is also of great importance in this connexion. Whether a positive is always formed paired with a negative, or whether a positive not accompanied by a negative can in some cases be produced, is a question difficult to answer from the data so far obtained. An accurate calculation of the probability of removal of the negative, if a pair is generated, so that only the positive emerges from the plate, is not simple to make, depending as it does on energy loss and plural scattering in the plate, and on the initial space and energy distribution of the components of the pairs. But on the basis of very approximate considerations, it appears somewhat difficult to reconcile

the appearance, for example, in the case of aluminum, of 20 single positives and only 7 pairs with the view that they are always formed in pairs. Experiments now planned in which the particles are ejected from very much thinner plates should decide this question. 中文

One case should be cited in which two negatives and two positives were all observed to originate at one point in the lead plate. The possibility that this can represent two pairs accidentally associated in time and position is so remote that it is taken as evidence that *photons of energy even so low as those of the thorium C" gamma-rays can occasionally give rise to showers such as are a common feature of the cosmic rays*⁹. 中文

Cosmic Ray Effects

Our recent stereoscopic photographs taken in a 17,000 gauss magnetic field show numerous showers of more than thirty electrons, some positives and some negatives, originating in lead plates placed across the chamber. In all the observed cases of shower production, it was clearly seen from the photographs that non-ionising particles produced the showers. Also photographs taken in a magnetic field of only 800 gauss showed many examples of single negatives, single positives, pairs and triplets, of energies of the order of only a million or two electron volts, ejected from plates of lead by the impact of non-ionising particles. These low energy ejections are in all respects identical with those produced by the thorium C" γ -rays and are undoubtedly due to low energy photons. These electron effects cannot be ascribed to ordinary neutrons since a considerable study of neutrons in this very range of energies has shown that their absorption results in projected nuclei and not in electron projection or shower formation. The appearance of several such small electron showers on one photograph which contains evidences of showers which occurred above the chamber, brings to light a new fact, namely, that *in the absorption of the cosmic rays there are produced, in addition to the*

electron showers, in some instances, sprays of large numbers of secondary photons. The evidences for this conclusion were presented at the November 1933 meeting of the National Academy of Sciences by Millikan, Neddermeyer, Pickering and myself¹⁹, and a full discussion together with the photographs will appear shortly in the *Physical Review*. In one case, more than eighty low energy electron tracks simultaneously projected were photographed, their positions and orientations in the chamber showing that they must have arisen from nearly as many separate centres in the material surrounding the chamber, and must therefore be ascribed to such a spray of secondary photons. [中文](#)

That pair production or shower formation by a fast electron (positive or negative) is a relatively rare event is shown by the fact that more than a thousand fast electrons have been observed to traverse a 1 cm. lead plate, and only in one instance was a definite pair projected from the lead by a fast electron, while a large number of secondary negative electron tracks appeared as the result of close encounters with the extra-nuclear electrons in the lead plate. The immediate secondaries of fast electrons are therefore seen to consist largely of negative electrons and only in rare cases of positrons. [中文](#)

Because of the powerful magnetic field we are using, it is possible to deflect all but a very small number of the electrons projected in the showers by the photon impacts. In general, in a shower a pronounced asymmetry is noted in the numbers of positive as compared with negative electrons emerging from the lead plates, in one instance 7 positives and 15 negatives, and in a second case 15 positives and 10 negatives. These effects are only with some difficulty reconciled with the Dirac theory of the creation of pairs out of the incident photon. Rather might they indicate the existence of a nuclear reaction of a type in which the nucleus plays a more active rôle than merely that of a catalyst, as for example the ejection from it of positive and negative

charges which then appear in the showers as free positive and negative electrons. The essential difference, however, between these two points of view may be merely that in one case the nucleus may change its charge, and in the other it does not do so. [中文](#)

To study nuclear absorption in a light element, more than four hundred successful photographs were taken in which a carbon plate of 1.4 cm. thickness replaced the lead plate. Many of these showed showers originating in a block of lead placed above the chamber, but in no instance was a secondary shower observed in the carbon plate. This indicates, in agreement with the thorium C'' data, the relatively small probability in comparison with lead of a carbon nucleus absorbing a photon by shower production. [中文](#)

A consequence of the pair-theory is that, in a suitably dense environment of negative electrons such as obtains in ordinary matter, a positron shall have a high probability of combining with a negative electron, resulting in the annihilation of both particles and the conversion of their proper and kinetic energies into radiation. The theory, though at present incomplete, states that the mean free path for annihilation is in general greater than the range of the positron, so that such annihilation should be evidenced by the appearance of quanta of about half a million electron-volts energy and a very small number of quanta of about one million electron-volts energy when positrons pass through matter²⁰. The experiments by Gray and Tarrant¹⁸ on the scattering of thorium C'' γ -rays showed the existence of secondary radiation of such energies, but some of the more recent experiments on the scattering of hard γ -rays fail to show a secondary radiation which can be attributed to the annihilation of positrons. Our cosmic ray photographs show that in the electron showers there are present large numbers of secondary photons, many of which are in this range of energy, but it is not yet certain if they are produced in part by the annihilation of positrons. In two very recent papers,

Joliot²¹ and Thibaud²² report the observation in experiments with artificially produced positrons of secondary photons of the energies to be expected if they arise from the annihilation of positrons. By control experiments with negative electrons, they showed that a beam of positrons impinging upon matter results in the production of a considerably greater quantity of photons than does an equal number of negative electrons. 中文

(133, 313-316; 1934)

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References:

1. Anderson, *Science*, **76**, 238; 1932.
2. Millikan and Anderson, *Phys. Rev.*, **40**, 325; 1932. See also Anderson, *Phys. Rev.*, **41**, 405; 1932; and Kunze, *Z. Phys.*, **80**, 559; 1933.
3. Anderson, *Phys. Rev.*, **43**, 491; 1933.
4. Millikan, *Science*, **78**, 153; 1933.
5. Blackett and Occhialini, *Proc. Roy. Soc., A*, **139**, 699; 1933.
6. Chadwick, Blackett and Occhialini, *Nature*, **131**, 473, April 1, 1933.
7. Curie and Joliot, *C.R.*, **196**, 1105; 1933.
8. Meitner and Philipp, *Naturwiss.*, **21**, 286; 1933.
9. Anderson, A.A.A.S. meeting, April 28, 1933, and *Science*, **77**, 432; 1933.
10. Anderson and Neddermeyer, *Phys. Rev.*, **43**, 1034; 1933.
11. Curie and Joliot, *C.R.*, **196**, 1581; 1933.
12. Meitner and Philipp, *Naturwiss.*, **24**, 468; 1933.
13. Curie and Joliot, *C.R.*, **197**, 237; 1933.
14. Oppenheimer and Plesset, *Phys. Rev.*, **44**, 53; 1933. Beck, *Z. Phys.*, **83**, 498; 1933.
15. Anderson, *Phys. Rev.*, **44**, 406; 1933.
16. Chao, *Proc. Nat. Acad. Sci.*, **16**, 431; 1930. *Phys. Rev.*, **36**, 1519; 1930.
17. Meitner and Hupfield, *Naturwiss.*, **19**, 775; 1931.
18. Gray and Tarrant, *Proc. Roy. Soc., A*, **136**, 662; 1932.
19. Anderson, Millikan, Neddermeyer and Pickering, *Proc. Nat. Acad. Sci.* Autumn meeting Nov. 20, 1933. See also abstract by Anderson and Neddermeyer, A.A.A.S. meeting, Dec. 30, 1933.
20. Fermi and Uhlenbeck, *Phys. Rev.*, **44**, 510; 1933.
21. Joliot, *C.R.*, **197**, 1623; 1933.
22. Thibaud, *C.R.*, **197**, 1629; 1933.

* Address delivered at the Symposium on Nuclear Physics of the American Physical Society meeting in Boston, Mass., on December 27, 1933.

正电子*

安德森

1932年9月，卡尔·安德森声明发现了正电子，一种与电子质量相同且带有一个正电荷的粒子。在这篇文章中他回顾了正电子的发现和从那时起所学到的知识。他指出，通过宇宙线轰击铅靶并在强磁场内的云室中观察产生的径迹，便可确认这一发现。1933年4月，另有物理学家发现，在核的强场中 γ 射线可产生电子-正电子对。安德森详细地回顾了这些实验，并指出相反的过程应该也是非常重要的，即电子和正电子的湮灭产生 γ 辐射，尽管这一现象当时还未被观测到。

[英文](#)

1932年9月，根据在加州理工学院进行的宇宙线实验，我本人首次报道了自由正电子或者正电子的存在^[1]。对于发生的那些效应，所有可能的解释都在这篇最初的文章中进行了详细讨论，该文还指出只有通过引入自由正电子的存在，才能从逻辑上解释那些效应。

[英文](#)

作为密立根教授的宇宙线研究计划（具体来说就是利用在非常强的水平磁场内的垂直云室做宇宙线粒子能量的测量）的一部分，这种测量于1931年8月首次拍得照片，当时的装置情况是云室17 cm $\times$ 17 cm $\times$ 3 cm，磁场强度保持在20,000高斯。正如1931年11月在巴黎和英国剑桥的讲座中所报道的，以及密立根和我本人^[2]于1932年3月发表的结果一样，这项研究首次揭示了一个事实，即在宇宙线的吸收过程中核效应是最重要的。伴生的带正电荷和负电荷的粒子的径迹或簇射的频繁发生可以证明这一点。

[英文](#)

1932年5月将铅板插入云室中心的实验能够明确说明，在几种情况下，这些带正电荷的粒子的质量不可能像质子的质量那么大。这些粒子的运动方向可以由以下两个过程来确定：首先，允许它们通过铅板，并

损失部分能量；随后，对同样来自云室周围物质中某个小区域的两条或多条径迹进行观测。对于一条给定曲率的径迹，比电离显示该粒子的质量小于质子质量，而从粒子射程的观测则获得了更加确定的证据。所观测到的该粒子的射程是相同曲率的质子径迹的可能射程的好几倍，在某些情况下甚至超过了10倍。 [英文](#)

1932年9月发表的宣称自由正电子或正电子存在的报道正是基于上述思考。在此后的五个月内又拍摄到了大量的验证性照片，这些照片明确地揭示了正电子的存在。1933年3月刊登的第二篇报道^[3]对其中的15张照片进行了探讨。这些照片上的正电子径迹所展现出的比电离显示，正电子的电荷大小与自由负电子的电荷大小相差不到两倍。因此除非我们允许电荷的基本单位为分数值，否则我们可以断定自由正电子和负电子的电荷大小是完全相同的。根据这个事实，连同在磁场中正电子穿透铅板前后测量到的曲率一起，就可以确定出其质量不会比自由负电子的质量高出20倍。 [英文](#)

上述结论得出之后^[4]，对发生在云室气体中的一个运动正电子和一个自由负电子间的碰撞的观测表明，根据守恒定律，正电子的质量和自由负电子的质量是相等的，其误差不超过30%。通过在磁场中的径迹上进行真实离子计数，得到的与高速和低速的正负电子的比电离有关的更多最新测量结果^[15]表明，正电子和负电子的比电离差别不会超过20%。这样就确定了对于电荷和质量，正电子和负电子的最大差值分别为10%和20%。有关这个发现过程的更多细节发表于1933年6月在美国芝加哥举行的美国科学促进会的会议上^[4]。 [英文](#)

1933年3月，基于运行在3,000高斯磁场内的垂直云室中的类似实验，并利用盖革-米勒计数器的响应来启动云室，布莱克特和奥恰利尼^[5]给出了正电子存在的确定性证据。1933年4月，查德威克、布莱克特和奥恰利尼^[6]、居里和约里奥^[7]以及迈特纳和菲利普^[8]均指出，用 α 粒子对铍进行轰击可以产生辐射，从而导致正电子的产生，不过这些实验尚不能完全确定产生正电子的辐射的本质。然而通过吸收实验，居里和约里奥指出，如果正电子的产生是 γ 射线而不是辐射的中子组分造成的，那么产生的正电子的数量大体上会像预期中的那样减少。 [英文](#)

首批直接证明 γ 射线光子撞击原子核会产生正电子的实验是在诺曼桥实验室进行的。该实验发表于1933年4月^[9]，所使用的 γ 射线来源于钍C”。这篇文章首次报道了具有重要理论意义的观测，即用单个 γ 射线光子的碰撞会同时产生带有正电和负电的自由电子。1933年6月，尼德迈耶和笔者^[10]给出了能量测量的初步结果。居里和约里奥^[11]以及迈特纳和菲利普^[12]分别于1933年5月和1933年6月，采用了钍C”的 γ 射线，并同样报道了从 γ 射线源可检测到正电子。居里和约里奥^[13]还指出，经 α 粒子轰击后在铝和硼的蜕变中可直接产生正电子。就铝而言，这里的正电子不能由 γ 射线光子的内转换来产生，除非这种内转换的概率远大于理论预期值^[14]。这些实验确实能够表明，基本正电荷实际上是从蜕变的原子核中转移出来的，并表现为一个正电子。 [英文](#)

前面的论述简要地回顾了有关正电子及其产生的早期实验工作。

[英文](#)

用过滤的钍C”的 γ 射线对自由正电子和负电子对的能量分布和产生频率进行详细研究具有特殊的价值，因为这些效应与在宇宙线能区出现的效应相比较为简单。 [英文](#)

γ 射线效应

现在将就支持布莱克特和奥恰利尼的理论的实验证据进行讨论，该理论以狄拉克的电子理论为基础，它假设光子撞击原子核的吸收过程会产生出一个自由的正负电子对。在此图像中，核本身不发生蜕变，而只是起催化剂的作用。讨论将依据以下两点：（1）由尼德迈耶和笔者对钍C”的 γ 射线效应所进行的新的统计研究；（2）由密立根、尼德迈耶、皮克林和笔者对宇宙线簇射所做的新实验。 [英文](#)

居里和约里奥以及查德威克、布莱克特和奥恰利尼关于钍发出的辐射和用 α 粒子轰击铍而激发出的辐射的研究，以及我们关于宇宙辐射的研究^[15]综合表明，产生正电子的吸收过程随着高能辐射和高吸收材料的发展而变得越来越重要。此外，我们基于总共超过2,500条单电子（包括正电子和负电子）和正负电子对的径迹进行了统计研究，这些单电子和电子对是由放射性钍通过2.5 cm厚的铅板过滤得到的 γ 射线照射

铅板、铝板和石墨板而发射出来的（某些情况下会使用未过滤的射线以进行比较）。通过该研究可测定正负电子对和单个正电子产生的频率，以及它们对不同原子序数的吸收物质的能量分布。我们的观测中采用的是0.25 mm厚的铅板、0.5 mm厚的铝板和1.4 cm厚的石墨板（它们也同样被用于宇宙线的研究）。所使用的磁场为825高斯。 [英文](#)

我们首先来考虑能量。从铅板上发射出来的单个正电子和电子对（取正负电子的能量之和）所显示的最大能量均约为1.6 MV（MV=兆电子伏），80%的单个正电子的能量小于0.8 MV。与使用过滤的射线的情况相比，在未使用过滤的 γ 射线的情况下，尽管发射出来的正电子和电子对的数量相对较少，但最大能量也显示为1.6 MV。此外，在使用铝板的情况下，发射出的正电子和电子对的最大能量也约为1.6 MV。

[英文](#)

在所有情况下，单个负电子的最大能量都约为2.5 MV。由于能量测量中的误差可能高达15%，因此其与康普顿碰撞或2.65 MV光子的光电吸收后产生的核外电子的最高预期能量符合得很好。 [英文](#)

如果1 MV是产生一个电子对所需要的能量，那么来自铅和铝的正电子和电子对的最大能量1.6 MV就能与狄拉克图像的预期很好地吻合。然而，产生一个电子对所需的总能量是2.9 MV；虽然不太可能，但可以想到的是，它也许已经由宇宙线产生，再或许是它表示了一个电子对铅板下表面的反弹。 [英文](#)

与能量分布同等重要的是，与单个负电子相比，单个正电子及电子对的数目分布。放射性钷通过2.5 cm厚的铅板过滤得到的 γ 射线照射0.25 mm厚的铅板，总共可发射出1,542个电子，其中有1,387个单个负电子、96个单个正电子和59个电子对。用相同的 γ 射线照射0.5 mm厚的铝板，总共有943个电子径迹，其中916个单个负电子、20个单个正电子和7个电子对。 [英文](#)

通常可以认为负电子源于铅或铝中核外电子的康普顿碰撞和光电碰撞。但是单个正电子和电子对必然都对应于核的碰撞。如果我们假定在一般情况下由核碰撞产生的正负电子个数相等，那么我们便可以计算出核吸收与核外吸收之间的比值。对铅板而言，这个值约为20%，而对铝

板而言约为50%。这些值与赵忠尧^[16]、迈特纳^[17]及格雷和塔兰特^[18]在关于铅的吸收远超过铝的吸收以及在两种金属中核吸收与核外吸收的普遍关系的研究中采用完全不同的方法得到的值相当吻合。 [英文](#)

钷C^γ射线照射石墨板时，碳的核吸收是非常小的，这可以通过以下事实体现出来，即产生了415个负电子的同时，只出现了2个电子对和6个单个正电子。 [英文](#)

总的来说，来自铝和铅的正电子和电子对的能量关系，似乎与有关电子对产生的假说非常一致，同样也与基于这个假说而计算得到的在铅和铝中的过剩吸收的近似值相一致。 [英文](#)

就能量关系而言，观测到的单个正电子的数目与电子对数目之比也是非常重要的。一个正电子形成的同时是否总是伴随着一个负电子的形成，或者在某些情况下是否正电子产生的同时不伴随负电子的产生，这是一个难以通过目前所掌握的数据来回答的问题。当一个电子对产生时，板中只发出正电子，这时要对负电子移出概率进行精确计算并不容易，因为这受到多种因素的影响，其中包括发生这种情况时在板内的能量损失和多次散射，以及电子对组分的起始空间和能量分布。但是根据非常粗略的分析，结果似乎很难与实际情况相符，例如，对铝而言，有20个单个正电子，另外仅有7个电子对，而理论上来说它们应该总是成对出现的。在现在计划进行的实验中，粒子将从很薄的板上发射，这应当能对这个问题做出判定。 [英文](#)

应当指出的一个例子是，实验中观测到两个负电子和两个正电子都在铅板的同一点产生。这表明在时间和位置上偶然出现关联的两个电子对的概率是极低的，因此这个现象可以证明，即使能量像钷C^γ射线那样低的光子偶尔也会产生簇射，如同宇宙线所具有的普遍特征一样^[9]。 [英文](#)

宇宙线效应

我们最近在17,000高斯的磁场中拍摄的立体照片显示，大量多于30个电子的簇射（有些是正电子，有些是负电子）产生于穿过云室放置的铅板上。从照片中可以清楚地看到，在所有观测到的产生簇射的情况

中，仅非电离粒子产生簇射。同样在仅为800高斯的磁场中拍摄的照片也显示了许多通过非电离粒子的碰撞，从铅板发射出单个负电子、单个正电子、电子对和三电子组的例子，它们的能量量级仅为1或2兆电子伏。这些低能的发射物在各个方面都与那些铀C²³⁸的γ射线产生的发射物一致，并且无疑是由于低能光子产生的。这些电子效应不能归属于普通的中子，因为对这个能区的中子的大量研究已经表明，它们的吸收会导致核的发射，而不是电子的或簇射的形成。在一张照片中有几个这样的小型电子簇射的出现，这也在云室之上出现簇射的证据，这一现象揭示了一个新的事实，即在宇宙线的吸收中，除了电子簇射之外，在某些情况下，还会产生大量次级光子的喷射。密立根、尼德迈耶、皮克林和笔者^[19]于1933年11月在美国国家科学院的会议上给出了此结论的相关证据，结合这些照片所做的一个全面的讨论也将于近期发表在《物理学评论》上。在其中一个示例中，超过80个同时发射的低能电子的径迹被拍摄下来，它们在云室中的位置和方向表明，它们一定产生自包围云室的材料的许多分立中心，因此这一定是由次级光子的喷射而产生的。

英文

由快电子（正的或负的）产生电子对或形成簇射是相当罕见的事件，这可由以下事实说明，观测到多于1,000个快电子穿过1 cm厚的铅板，仅有一例确定是从铅板上由快电子射出的电子对，而大量的次级负电子径迹似乎均为在铅板中与核外电子近距离碰撞的结果。因此快速电子的即时次级发射似乎是由大量负电子构成的，而正电子仅是不多见的情况。

英文

由于我们所用的磁场很强，因此除了由光子碰撞产生的簇射中发射出的极少量的电子没有发生偏转外，可能所有的电子都发生了偏转。通常在一个簇射中可注意到，从铅板发射出的正电子数目与负电子数目明显不对称。其中一个簇射中，有7个正电子和15个负电子，而在另一个簇射中，则有15个正电子和10个负电子。这些效应遭遇的唯一困难是，很难与入射光子产生电子对的狄拉克理论取得一致。很可能这些效应表明存在一类核反应，其中核的作用不仅是催化剂而是比之更加活跃，例如，正电荷和负电荷从核中发射出来，然后作为自由正电子和负电子出现在簇射中。然而，这两种观点本质上的区别可能只不过是，其中一个

认为核是可以改变其电荷的，而另一种观点则认为其电荷不会改变。

英文

为了研究在轻元素中的核吸收，于是将铅板替换为1.4 cm厚的碳板并成功地拍摄了400多张照片。许多照片显示出，位于云室上面的铅块中会产生簇射，但在所有情况下都没有在碳板上观测到次级簇射。这与钍C"的数据得出的结论一致，即与铅相比，碳核经由簇射产生吸收光子的概率较小。 英文

电子对理论的结论是，在负电子适当稠密的环境中（如同在普通物质中存在的那种），正电子与负电子有很高的概率相互结合，从而导致两种粒子的湮灭，而它们的固有能量和动能将转换为辐射。尽管这种理论目前还不完善，但它表明发生湮灭的平均自由程通常大于正电子的射程，因此，当正电子通过物质时，这类湮灭应当可以通过具有大约0.5兆电子伏能量的量子以及少量具有约1兆电子伏能量的量子的出现来证实[20]。格雷和塔兰特^[18]关于钍C"的 γ 射线的散射实验显示，存在具有这种能量的次级辐射，但在最近的一些硬 γ 射线的散射实验中却没有观测到次级辐射，这可以归因于正电子的湮灭。我们的宇宙线照片表明，在电子簇射中存在大量的次级光子，其中许多是在这个能区中，但还不能确定它们是否部分地产生于正电子的湮灭。在最近的两篇文章中，约里奥^[21]和蒂博^[22]报道了如果次级光子是由于正电子的湮灭产生的，则观测利用预期能量的次级光子人工产生正电子的实验是可行的。通过用负电子控制实验，他们表示，与相同数量的负电子相比，一束正电子与物质碰撞时所产生的光子要多很多。 英文

（沈乃澂 翻译；张焕乔 审稿）

* 本演讲发表于1933年12月27日在美国马萨诸塞州波士顿举行的美国物理学会会议的核物理分会会上。

Production of Induced Radioactivity by High Velocity Protons

J. D. Cockcroft *et al.*

By the mid 1930s physicists were routinely producing new radio-isotopes by bombarding elements with alpha particles and protons. Here Cockcroft and colleagues describe the bombardment of graphite with high-energy protons, producing radioactivity that decreases with a half-life of about ten minutes. This suggested that the proton beam had created a significant amount of some radionuclide, presumably ^{13}N . Some of the emitted particles were positrons, although most were ordinary electrons with high energies that might be explained as due to “kicks” by gamma rays. These in turn might have been created by annihilation of positrons in the chamber walls. This was among the first observations of electron–positron annihilation, a process that was not well understood until the 1940s. [中文](#)

CURIE and Joliot¹ have reported that a number of new radioactive isotopes can be produced by the bombardment of various elements with α -particles, these isotopes emitting positive electrons. In particular, they showed that boron when bombarded by α -particles was transformed to the isotope N^{13} , radio-nitrogen, this isotope having a half life of 14 minutes. They suggested that the isotope might be

produced by the bombardment of carbon with heavy hydrogen, the product, N^{14} , disintegrating with the emission of a neutron to radio-nitrogen. [中文](#)

We have bombarded a target of Acheson graphite with *protons* of 600 k.v. energy and have used a Geiger counter to search for any radiations produced after the bombardment ceased. After bombardment for 15 minutes with a current of about 10 microamperes of protons, the target was removed from the apparatus and placed against the Geiger counter. We then observed about 200 counts per minute, being about forty times the natural effect. The number of counts decayed exponentially with time, having a half life of 10.5 ± 0.5 minutes. [中文](#)

We then carried out an experiment similar to that performed by Becquerel, in which the source was placed on one side of a 9 mm. thick lead plate with the counter on the opposite side, the whole being placed in a magnetic field, so that any electron emitted could only reach the counter by applying a field of appropriate sign and magnitude. We found that when the field was such that positive electrons could reach the counter, the number of counts increased by a factor of 3; when the field was in the reverse direction no definite increase was observed. We conclude, therefore, that the radiations consist in part at least of positive particles. [中文](#)

We have also taken about 250 Wilson chamber photographs in a field of 2,000 gauss, placing the activated source against the outside of the chamber wall, which was about 3 mm. thick. Under these conditions, we observed only two electrons of positive curvature which could possibly have come from the source, these electrons having energies of the order of 500 k.v. We observed, on the other hand, 48 tracks of Compton electrons starting in the gas, having energies ranging from 100 k.v. to 500 k.v., suggesting the emission of γ -rays of energy between 500 k.v. and 1 million volts. These γ -rays may result from the

annihilation of the positive electrons, presumably in the glass wall of the chamber. The deflection experiments, whilst not at present precise, tend to confirm that few of the positive electrons would have sufficient energy to penetrate the glass walls. Further experiments will, therefore, be carried out with the source inside the chamber.*

[中文](#)

The observations suggest that the unstable isotope N^{13} is produced by the addition of a proton to C^{12} . The difference between the half life observed and that reported by Curie and Joliot may be due to the formation of N^{13} in a different excited state. [中文](#)

No marked increase in the number of counts was observed when a mixed beam of heavy hydrogen ions and protons was substituted for the proton beam. [中文](#)

We are very much indebted to Dr. K. T. Bainbridge, who supplied the Geiger counter with which the observations were made. [中文](#)

(133, 328; 1934)

J. D. Cockcroft, C. W. Gilbert and E. T. S. Walton: Cavendish Laboratory, Cambridge, Feb. 24.

Reference:

1. *Comptes rendus*, **198**, 254; 1934.

* February 27. Experiments carried out with a counter having a mica window of small stopping power gave a great increase in the number of counts owing to the positive electrons now entering the counter. The absorption curve of the positive electrons is similar to that of negative electrons of 800 k.v. energy.

由高速质子产生的感生放射性

考克饶夫等

直到20世纪30年代中期，物理学家通常使用 α 粒子和质子轰击多种元素以产生新的放射性同位素。这篇文章中考克饶夫和他的合作者们描述了一种使用高能质子轰击石墨的实验，该实验产生了以半衰期约为10分钟的速率衰减的放射性。这表明质子束产生了某种数量可观的放射性核，有可能是 ^{13}N 。发射出来的粒子中有一些是正电子，当然，大部分是高能的普通电子，普通电子可以解释为是由 γ 射线引起的“反冲”造成的。反之 γ 射线可能是由于正电子在云室壁上湮灭产生的。这是首次观察到的电子-正电子湮灭现象之一，而这一过程直到20世纪40年代才被人们很好地理解。 [英文](#)

居里和约里奥^[1]曾经报道，许多新的放射性同位素可以用 α 粒子轰击各种元素来获得，这些同位素会放射出正电子。他们特别指出，当用 α 粒子轰击硼时，硼会转变为氮的同位素 ^{13}N ，即放射性氮，这种同位素的半衰期是14分钟。他们认为，有可能通过重氢轰击碳产生的 ^{14}N 在放出一个中子后衰变为这种放射性氮。 [英文](#)

我们用600千电子伏能量的质子对艾奇逊人造石墨靶进行了轰击，并使用盖革计数器探测在轰击停止后产生的辐射。用强度约为10微安的质子流轰击15分钟后，将石墨靶从装置上移开并放置在正对着盖革计数器的地方。这时，我们观测到的计数约为每分钟200个，约为正常值的40倍。计数随时间呈指数衰减，其半衰期为 10.5 ± 0.5 分钟。 [英文](#)

然后，我们做了一个与贝克勒尔所做实验类似的实验，在这个实验中，放射源放在9mm厚的铅板一侧，计数器放置在另一侧，整个装置放在磁场内，只有当磁场的方向和大小都合适时，发射出来的电子才能到达计数器。我们发现，当磁场能使正电子到达计数器时，计数增加到原

来的3倍；当磁场反向时，未观测到计数的明显增加。因此我们认为，至少部分辐射是由带正电的粒子组成的。 [英文](#)

在2,000高斯的磁场中，我们将活化后的放射源放在约3mm厚的云室壁的外侧，并拍摄了250张威尔逊云室的照片。在这种条件下，我们只观测到了两条正曲率的电子径迹，这些径迹可能是由放射源发射出的粒子形成的，而这些电子的能量在500千电子伏的数量级上。另一方面，我们观测到了从气体中发出来的48条康普顿电子的径迹，其能量分布在100千电子伏到500千电子伏的范围内，这表示 γ 射线的发射能量范围在500千电子伏与1兆电子伏之间。这些 γ 射线可能是由于正电子的湮灭而产生的，这一过程很可能发生在云室的玻璃壁内部。尽管偏转实验目前并不精确，但它仍然倾向于肯定少量的正电子将具有足够的能量穿透玻璃壁。因此，下一步的实验将把放射源置于云室内进行。* [英文](#)

观测到的这些现象表明，不稳定的同位素 ^{13}N 是由于 ^{12}C 增加一个质子而产生的。我们观测到的半衰期与居里和约里奥报道的数据不同，这可能是由于形成的 ^{13}N 处于不同的激发态。 [英文](#)

当我们用重氢离子与质子的混合束代替质子束时，并未观测到计数的明显增多。 [英文](#)

我们非常感激班布里奇博士，他提供了我们实验必需的盖革计数器。 [英文](#)

（沈乃澍 翻译；夏海鸿 审稿）

* 2月27日，在使用具有微小制动力的云母窗口计数器的实验中，正电子的进入使得计数器的数量极大地增加。正电子的吸收曲线与800千电子伏能量的负电子的吸收曲线相似。

Designation of the Positive Electron

H. Dingle

As of 1934 there was no consensus about how to name the positive electron, discovered two years earlier. The popular (and ultimately the prevalent) choice seemed to be “positron”, against which Herbert Dingle here argues. It is ugly and offends the literary sense with its hybrid character, he says, and moreover it suggests that the electron ought to be unhappily renamed the “negatron”. Dingle suggests instead the poetic name “oreston”, alluding to the sister and brother Elektra and Orestes of Greek myth. It never caught on. [中文](#)

I have been hoping that, following Lord Rutherford’s proposal of a name for the heavy isotope of hydrogen, someone would suggest a more satisfactory word than “positron” for the positive electron. Since, however, no better qualified reformer has appeared, may I raise the question before it is too late? “Positron” is ugly; it offends literary purists by its hybrid character; and it not only bears no relation to the established name of the associated particle, the electron, but even suggests that that particle should be called the “negatron”, which fortunately it is not. [中文](#)

In order to balance destructive by constructive criticism, I venture to propose the name “oreston” for the newcomer. The word is

euphonious, pure Greek, and since, in one of the most beautiful of Greek stories, Orestes and Elektra were brother and sister, it implies an appropriate relation between the two particles. The name found favour among many physicists in Pasadena where Anderson first obtained evidence of the particle, when I mentioned it there last year. I do not propose, however, further to urge its claims, the purpose of this letter being mainly to cleanse the language of “positron”, and only incidentally to nominate a substitute. 中文

(133, 330; 1934)

Herbert Dingle: Imperial College, South Kensington, S.W.7, Feb. 12.

正电子的命名

丁格尔

截至1934年，物理学家对于两年前发现的带正电的电子的命名问题仍未达成一致。通常情况下（也是极为普遍的）会使用“positron”（正电子）一词，而这篇文章中赫伯特·丁格尔就此发表了反对意见。他认为这个单词是丑陋的，这种复合词的方式违背了文学的原则，此外，这还意味着“electron”（电子）应该不幸地被重命名为“negatron”。丁格尔建议代之以一个更加诗意的名字“oreston”，暗指希腊神话中的厄勒克特拉和俄瑞斯忒斯姐弟。然而这个名字并未流行起来。 [英文](#)

在卢瑟福勋爵提议给氢的重同位素命名之后，我一直希望有人可以给带正电的电子起一个比“positron”更令人满意的名字。不过既然目前仍没有人给出更好的新命名，我是否可以在这里及时地提出这一问题？坦白而言，“positron”这个单词是丑陋的；它采用的复合词的形式在文学纯化论者看来是很反感的事情；它不仅与相关的粒子，即电子已确定的名字没有什么关系，甚至还容易让人以为电子（electron）应该被称为“negatron”，不过幸好大家没有这么做。 [英文](#)

为了早日改变这一现状，在此我大胆建议为刚发现的带正电电子采用一个新的命名“oreston”。这个词非常悦耳并且是纯希腊语，此外还因为在最动听的希腊故事之一中，厄勒克特拉和俄瑞斯忒斯是亲姐弟，因此采用这一命名可以恰当地表达这两种粒子之间的关系。帕萨迪纳是安德森首次证实新粒子存在的地点，去年，当我在那里提议采用这个名字的时候，那里的物理学家都很赞成。然而，我并不会进一步要求大家非要接受这一命名。事实上，本文的主要目的是想消除“positron”这一命名，并顺便推荐我的命名。 [英文](#)

(金世超 翻译；朱永生 审稿)

Transmutation Effects Observed with Heavy Hydrogen

M. L. Oliphant *et al.*

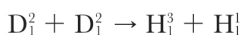
While American physicists were calling the recently discovered isotope of hydrogen “deuterium”, their British colleagues persisted with “diplogen”. Here Mark Oliphant and Paul Harteck, working with Rutherford in Cambridge, describe experiments that seem to involve the reaction of two diplogen nuclei (“diplons”). They substituted diplogen for hydrogen in ammonium compounds and bombarded them with low-energy diplogen. The researchers note that if two diplogen nuclei combine to form a helium nucleus, its atomic mass would be slightly greater than the known atomic mass of helium. So the resulting nucleus would be highly unstable and would immediately decay, throwing out protons and neutrons. Identifying the putative decay products (helium-3 and hydrogen-3, or tritium) awaited further experimental refinement. [中文](#)

WE have been making some experiments in which diplons have been used to bombard preparations such as ammonium chloride (NH_4Cl), ammonium sulphate ($(\text{NH}_4)_2\text{SO}_4$) and orthophosphoric acid (H_3PO_4), in which the hydrogen has been displaced in large part by diplogen. When these D compounds are bombarded by an intense beam of protons, no large differences are observed between them and the ordinary hydrogen compounds. When, however, the ions of heavy

hydrogen are used, there is an enormous emission of fast protons detectable even at energies of 20,000 volts. At 100,000 volts the effects are too large to be followed by our amplifier and oscillograph. The proton group has a definite range of 14.3 cm., corresponding to an energy of emission of 3 million volts. In addition to this, we have observed a short range group of singly charged particles of range about 1.6 cm., in number equal to that of the 14 cm. group. Other weak groups of particles are observed with the different preparations, but so far we have been unable to assign these definitely to primary reactions between diplons. [中文](#)

In addition to the two proton groups, a large number of neutrons has been observed. The maximum energy of these neutrons appears to be about 3 million volts. Rough estimates of the number of neutrons produced suggest that the reaction which produces them is less frequent than that which produces the protons. [中文](#)

While it is too early to draw definite conclusions, we are inclined to interpret the results in the following way. It seems to us suggestive that the dipton does not appear to be broken up by either α -particles or by proton bombardment for energies up to 300,000 volts. It therefore seems very unlikely that the dipton will break up merely in a much less energetic collision with another dipton. It seems more probable that the diptons unite to form a new helium nucleus of mass 4.0272 and 2 charges. This nucleus apparently finds it difficult to get rid of its large surplus energy above that of an ordinary He nucleus of mass 4.0022, but breaks up into two components. One possibility is that it breaks up according to the reaction

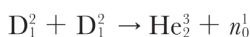


The proton in this case has the range of 14 cm. while the range of 1.6 cm. observed agrees well with that to be expected from momentum relations for an H_1^3 particle. The mass of this new hydrogen isotope

calculated from mass and energy changes is 3.0151.

[中文](#)

Another possible reaction is



leading to the production of a helium isotope of mass 3 and a neutron. In a previous paper we suggested that a helium isotope of mass 3 is produced as a result of the transmutation of Li^6 under proton bombardment into two doubly charged particles. If this last reaction be correct, the mass of He_2^3 is 3.0165, and using this mass and Chadwick's mass for the neutron, the energy of the neutron comes out to be about 3 million volts. From momentum relations the recoiling He_2^3 particle should have a range of about 5 mm. Owing to many disturbing factors, it is difficult to observe and record particles of such short range, but experiments are in progress to test whether such a group can be detected. While the nuclei of H_1^3 and He_2^3 appear to be stable for the short time required for their detection, the question of their permanence requires further consideration.

[中文](#)

(133, 413; 1934)

M. L. Oliphant, P. Harteck and Rutherford: Cavendish Laboratory, Cambridge, March 9.

通过重氢观察到的嬗变效应

奥利芬特等

当美国物理家们将新发现的氢的同位素（氘）称为“deuterium”的时候，他们的英国同行则坚持使用“diplogen”这一叫法。这篇文章中，马克·奥利芬特和保罗·哈特克在剑桥同卢瑟福合作，描述了一个似乎包含两个氘原子核（“氘核”）反应的实验。他们用氘置换铵化合物中的氢，然后用低能的氘去轰击它们。研究者们指出，如果两个氘核结合在一起形成一个氦核，那么这个氦核的原子质量会比已知的氦的原子质量略大。所以该反应得到的原子核会是高度不稳定的，并且会立即开始衰变，放出质子和中子。对假定衰变产物（氦-3和氢-3，后者或称为氚）的鉴别有待进一步的实验改进。

英文

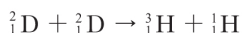
我们进行了以下的实验，用氘核轰击氯化铵（ NH_4Cl ）、硫酸铵（ $(\text{NH}_4)_2\text{SO}_4$ ）、正磷酸（ H_3PO_4 ）等样品，使得化合物中的大部分氢被氘置换。当这些氘化合物受到强的质子束轰击时，这些化合物和普通氢化合物没有表现出太大区别。然而，当用重氢离子轰击时，即便是在20,000电子伏的能量下也能探测到大量快质子发射。在100,000电子伏时，这个效应则太强以致于我们的放大器和示波器不能对其进行跟踪。质子群有14.3厘米的固定射程，对应3兆电子伏发射能量。除此之外，我们还观察到了一个射程约1.6厘米的单电荷粒子群，数量和14厘米的质子群相同。在不同的样品中，还观测到了其他弱的粒子群，但是到目前为止，我们还不能确定这些反应就是氘核之间的初级反应。

英文

除了这两个质子群，我们还观察到了大量的中子。这些中子中能量最大的约为3兆电子伏。对产生中子数目的粗略估算表明，产生中子的反应比产生质子的反应的频度要低。

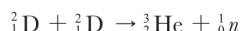
英文

现在得出确切的结论还为时过早，我们倾向于用以下方式来解释这些结果。当能量高达300,000电子伏时，无论用 α 粒子轰击还是用质子轰击，氘核都不会发生破裂，这对我们来说似乎是具有启发性的。因此，当氘核在更小的能量下与另一个氘核发生碰撞时，似乎就更不可能发生破裂了。更有可能的是，两个氘核结合而形成一个新的氦核，其质量为4.0272，电荷数为2。这个新的原子核的过剩能量比质量为4.0022的普通氦核的大，这一过剩能量明显是很难去除的，除非分裂为两部分。一种可能性是按照以下的反应发生分裂：



在这种情况下质子的射程是14厘米，而我们所观察到的1.6厘米的射程与根据动量关系估算出的 ${}^3_1\text{H}$ 粒子的射程吻合得很好。从质能关系计算得到这种新的氢同位素的质量为3.0151。 [英文](#)

另一种可能发生的反应是：



其产生一个质量为3的氦同位素和一个中子。在之前的一篇文章中，我们指出， ${}^6\text{Li}$ 被质子轰击后会转变为两个带双电荷的粒子，这样就产生了质量为3的氦同位素。如果最后的这个反应是正确的，那么 ${}^3_2\text{He}$ 的质量应为3.0165，利用这个质量和查德威克给出的中子质量进行计算，得出中子的能量约为3兆电子伏。根据动量关系，反冲的 ${}^3_2\text{He}$ 粒子的射程应该约为5毫米。由于存在很多干扰因素，观测并记录这样短射程的粒子是困难的，但是正在进行中的实验正试图去探测这样的粒子群。在探测所需的短时间内， ${}^3_1\text{H}$ 和 ${}^3_2\text{He}$ 原子核似乎是稳定的，它们的持久性问题还需要更进一步地探讨。 [英文](#)

（王静 翻译；张焕乔 审稿）

Supraconductivity of Films of Tin

E. F. Burton

Superconductivity had been discovered in 1911 by Heike Kamerlingh Onnes, who found that solid mercury lost its electrical resistance when cooled within a few degrees of absolute zero. Other materials such as tin and lead were soon also found to be “supraconductors”, as they were then known, but there was no explanation for the phenomenon. Here E. F. Burton of the University of Toronto reported an important constraint on such a theory: a thin film of superconducting material such as tin loses its superconductivity when sandwiched between other materials that are not superconducting. Burton notes that the effect applies only to sufficiently thin superconducting films, less than a micrometre or so thick. [中文](#)

EXPERIMENTS on the relation of high frequency currents to the phenomenon of superconductivity led to work at Toronto with films of superconducting metals. The films (of tin) were produced by “tinning” the surface of fine wires which themselves were not superconducting: in the early experiments a coating of tin 2×10^{-4} cm. in thickness was “wiped” on constantan wire of 0.016 cm. diameter. In this way one obtains the equivalent of a thin cylinder of superconducting metal, and the resistance of the whole becomes zero below the transition temperature of the superconducting element used¹. [中文](#)

With the intention of studying further the effect of high frequency currents, samples of such coated wires were plated with other metals—for example, copper and nickel—which are not superconductors; an example of such a combination is constantan covered with tin and then plated with copper. The diameters of the wires forming the core were as follows: for constantan 0.056 cm., for copper 0.040 cm. and for nickel 0.045 cm. 中文

Preliminary experiments were carried out on these samples to confirm their reaction with respect to direct currents—the ordinary superconductivity test—and it was found that thin films of tin cease to show superconductivity when these films are themselves plated over with a film of a non-superconducting metal, for example, copper or nickel. This surprising result shows itself only with thin films, but a number of repetitions of the experiments renders the results unmistakable. The accompanying table shows the nature of the phenomenon: so far, only the superconductor tin has been tested in this way. 中文

No.	Sample	Thickness of Tin Film (cm. $\times 10^{-3}$)	Thickness of outer layer (cm. $\times 10^{-3}$)	Superconductive Action, direct current of 200 ma.
1a	Constantan-Tin	10	0	Transition point 3.69°K
1b	Constantan-Tin-Copper	10	100	Not superconducting at 2°K
2a	Copper-Tin	9	0	Transition point 3.58°K
2b	Copper-Tin-Copper	9	100	Not superconducting at 2°K
3a	Nickel-Tin	9	0	Transition point 3.42°K
3b	Nickel-Tin-Copper	9	100	Not superconducting at 2°K
4	Constantan-Tin	6.8	0	Transition point 3.49°K
5	Constantan-Tin	2	0	Transition point 2.48°K
6	Constantan-Tin-Copper	18	40	Not superconducting at 2°K
7	Constantan-Tin-Copper	4	20	Not superconducting at 2°K
8	Constantan-Tin-Nickel	15	30	Not superconducting at 2°K
9	Constantan-Tin(wiped)	90	0	Transition point 3.68°K
9a	Constantan-Tin-Copper	90	80	Transition point 3.44°K
10	Constantan-Tin (electro-plated)	200	0	Transition point 3.76°K
10a	Constantan-Tin-Copper	200	80	Transition point 3.73°K
11	Tin Wire	diameter	0.085	Transition point 3.77°K

中文

It is seen that as the film of tin increases in thickness, a point is reached at which the superconducting property of the tin film is not lost by surface plating. This phenomenon will undoubtedly be of importance in framing a satisfactory theory of superconductivity—a

consideration of utmost importance in dealing with metallic conduction. This work is being carried on by J. O. Wilhelm and A. D. Misener. [中文](#)

(133, 459; 1934)

E. F. Burton: McLennan Laboratory, University of Toronto, Feb. 17.

Reference:

1. E. F. Burton, "Superconductivity" (University of Toronto Press, and Oxford University Press), p. 70. J. C. McLennan, *Nature*, **130**, 879, Dec. 10, 1932.

锡膜的超导电性

伯顿

1911年海克·卡默林·昂内斯发现了超导电性，他发现当温度低至绝对零度附近几度时固体汞的电阻会消失。随后另外一些材料诸如锡和铅也很快被发现是“超导体”，正如此后人们所知道的那样，但是当时并未能就这一现象给出解释。这篇文章中，多伦多大学的伯顿指出了超导理论的一个重要的限制条件：超导材料例如锡膜如果被夹在两层非超导的材料之间时，会失去它的超导电性。伯顿还指出这个效应只适用于足够薄的超导薄膜，厚度应小于或者等于1微米。

[英文](#)

关于高频电流与超导电性现象之间关系的实验促成了在多伦多进行的对超导金属膜的研究。（锡）膜是在非超导材料制成的细线表面“镀锡”形成的：在早期的实验中，我们的是将厚度为 2×10^{-4} 厘米的锡的镀层“包裹”在直径为0.016厘米的康铜丝上。按这种方法，我们得到了一个等效的超导金属的薄圆筒，而且当温度低于所用超导元素的转变温度时，整个薄圆筒的电阻会变为零^[1]。

[英文](#)

为了进一步研究高频电流的效应，我们给这类镀丝样品镀上其他一些没有超导电性的金属，如铜和镍；例如，在镀了锡的康铜丝外再镀上铜，作为芯的几种金属丝的直径如下：康铜，0.056厘米；铜，0.040厘米；镍，0.045厘米。

[英文](#)

我们最初做的实验是为了证实这些样品对直流电的反应，即普通的超导电性测试，在实验中我们发现，当这些锡膜镀上非超导金属膜（例如铜或镍）时，它们就不再显示超导电性。虽然这个奇怪的结果只有在膜非常薄时才能得到，但多次的重复实验都倾向于表明这个结果正确无误。下表显示出这种现象的规律：到现在为止，我们只用这种方法对超

序号	样 品	锡薄膜的厚度 (厘米 $\times 10^{-5}$)	外层的厚度 (厘米 $\times 10^{-5}$)	超导作用, 200 mA 的直流电流
1a	康铜-锡	10	0	转变点 3.69 K
1b	康铜-锡-铜	10	100	2 K 时无超导
2a	铜-锡	9	0	转变点 3.58 K
2b	铜-锡-铜	9	100	2 K 时无超导
3a	镍-锡	9	0	转变点 3.42 K
3b	镍-锡-铜	9	100	2 K 时无超导
4	康铜-锡	6.8	0	转变点 3.49 K
5	康铜-锡	2	0	转变点 2.48 K
6	康铜-锡-铜	18	40	2 K 时无超导
7	康铜-锡-铜	4	20	2 K 时无超导
8	康铜-锡-镍	15	30	2 K 时无超导
9	康铜-锡 (焊接的)	90	0	转变点 3.68 K
9a	康铜-锡-铜	90	80	转变点 3.44 K
10	康铜-锡 (电镀的)	200	0	转变点 3.76 K
10a	康铜-锡-铜	200	80	转变点 3.73 K
11	锡线	直径	0.085	转变点 3.77 K

英文

我们发现，当锡膜厚度增加到一个点时，锡膜的超导性能不再因为表面镀层而丧失。这种现象对构造一个令人满意的超导理论无疑是极其重要的，这是处理金属电导时需要重点考虑的一个问题。威廉和麦色纳正在进行这项研究。

英文

(沈乃澂 翻译；郑东宁 审稿)

Persistent Currents in Supraconductors

K. Mendelssohn and J. D. Babbitt

Physicists in the early 1930s were struggling to understand superconductivity. Here Kurt Mendelssohn and J. D. Babbitt explored the surprising recent discovery by Walther Meissner and Robert Ochsenfeld that a superconductor expels magnetic flux from its interior. That finding confounded the expectation that persistent electrical currents in a superconductor would instead “capture” magnetic flux and sustain it even if the external magnetic field were removed. Yet the experiments reported here showed that the flux expulsion wasn’t perfect: some magnetisation remains inside superconducting tin. This was the first evidence of persistent “supercurrents”, although their value was only one-sixth of that predicted earlier. [中文](#)

UNTIL recently it was generally assumed that it was possible to predict, by the ordinary electromagnetic equations, the persistent current produced in a supraconductor cooled below the transition point in a constant external magnetic field after the field was switched off. Thus H. A. Lorentz¹ calculated the current induced in a supraconducting sphere, that is, the effective magnetic dipole when an external magnetic field is established. [中文](#)

According to results recently published by Meissner and Ochsenfeld²,

the matter is not so simple as might at first sight appear. Instead of the lines of force being “frozen in” as had been previously assumed would happen when a superconductor was cooled below the transition point in a magnetic field, it appeared that the field increased in the neighbourhood of the superconductor, which behaved as a body of zero permeability. If this were so, the flux of induction in the superconductor should be zero and one might expect, in contradistinction to the old view, that no persistent current or effective induced dipole would be produced by switching off the external field. [中文](#)

The following experiments seem to show that although superconductors do not conform to the older theory, neither do they behave as though they had zero permeability. [中文](#)

(1) A solid tin sphere of 1.5 cm. radius was cooled from 4.2°K. to 2.5°K. (the liquid helium was produced in a liquefaction apparatus utilising the expansion method of Simon) in a field of 70 gauss. When the field was switched off, the magnetic moment of the sphere was observed with a test coil. Its magnitude was about one sixth of that calculated according to the Lorentz equation. [中文](#)

The magnetic moment remained almost constant whilst the temperature of the sphere rose from 2.5° to 2.9°; with a further rise in temperature it decreased steadily, becoming zero at 3.7°, the normal transition point of tin. Plotting the magnetic moment against the temperature, one obtains a curve of similar shape to that found for the magnetic threshold values. [中文](#)

(2) The same sphere was cooled to 2.5° without any external magnetic field, a field of 230 gauss (higher than the threshold value at this temperature) was switched on and immediately switched off. The magnetic moment thus produced in the sphere at 2.5° was 8 percent greater than that produced in the previous experiment using 70 gauss,

but as the temperature rose it decreased and at 2.9° it reached the same value as the magnetic moment at this temperature in the previous experiment. From 2.9° to 4° the curve coincided with that found in experiment (1). [中文](#)

(3) Similar experiments to those described above were carried out with a hollow tin sphere of the same radius, the spherical space in the middle being equal in volume to one half the volume of the sphere. The magnetic moments produced in the hollow sphere were two to three times greater than those obtained with the solid sphere. [中文](#)

In all these experiments the magnetic field was produced by a cylindrical coil in the middle of which the sphere was placed, all iron being excluded. Although the field near the sphere was thus fairly homogeneous, we think it possible that the observed phenomena may be influenced by slight inhomogeneities of the external field. In a completely homogeneous field it would seem possible that the method of cooling might affect the results. In order to test this, we cooled the spheres from the poles and also from the equator. This did not seem to make any difference, the magnetic moment observed being of the same order of magnitude in either case. [中文](#)

As a result of these experiments, it seems certain that the effective permeability of substances when they become supraconducting decreases, as observed by Meissner and Ochsenfeld. On the other hand, it appears clear that under our experimental conditions the permeability does not vanish entirely, as might be expected in view of the almost infinite conductivity, or if it does vanish, it only does so in certain regions and not throughout the whole volume of the superconductor. [中文](#)

In conclusion, we would like to express our thanks to Mr. T. C. Keeley for his advice and assistance in various phases of the work. [中文](#)

K. Mendelssohn and J. D. Babbitt: Clarendon Laboratory, Oxford, Feb. 17.

References:

1. Comm. Leiden, Suppl., Nr. 50 b, 1924.
2. *Naturwiss*, **21**, 787; 1933.

超导体中的持续电流

门德尔松，巴比特

20世纪30年代早期，物理学家们正在费尽心力地研究超导电性的产生机制。这篇文章中，库尔特·门德尔松和巴比特探讨了近期瓦尔特·迈斯纳和罗伯特·奥克森费尔德的惊人发现——超导体将磁通量排除在外。在此之前人们猜想超导体中持续的电流应该能够“捕获”磁通量，并且即使外磁场被撤除，超导体中的磁通量也能够保持，但该发现否定了这一猜想。然而这篇文章中报道的实验显示磁通量的排除并不完全：超导态锡的内部仍保留有一定的磁化强度。这首次证明了持续的“超导电流”的存在，尽管它的大小只有之前预测值的1/6。 [英文](#)

直至不久前，人们仍然普遍认为，根据一般的电磁方程就可以预测：在恒定外磁场中将超导体冷却至转变温度之下，关闭磁场时会产生持续的电流。据此，洛伦兹^[1]计算出了超导球体中的感生电流，即在外磁场建立后的有效磁偶极。 [英文](#)

按照迈斯纳和奥克森费尔德^[2]最近公开发表的结果，事情并非如初看时那么简单。磁场中的超导体被冷却到转变点之下时，并不像我们以前假定的那样会将磁力线“冻结”，实验表明，超导体附近的磁场会增强，超导体表现得像一个完全的抗磁体。如果事实确实如此，那么超导体中的感应磁通量应为零，而且我们也可以推断出与旧观点相反的结论：关闭外磁场并不会在超导体中产生持续的电流或有效的感生偶极。

[英文](#)

下列实验似乎表明，超导体虽然并不符合旧的理论，但也没有表现出磁导率为零的性质。 [英文](#)

(1) 在70高斯的磁场中，将一个半径为1.5厘米的固体锡球的温度从4.2 K冷却到2.5 K (液氦是在一个液化装置中利用西蒙膨胀法产生的)。当关闭磁场时，我们用实验线圈测量固体球的磁矩。测量得出的磁矩大小约为根据洛伦兹方程计算所得值的1/6。 [英文](#)

当球的温度从2.5 K上升到2.9 K时，磁矩几乎保持恒定；而在温度进一步上升时，磁矩稳步减少，且在3.7 K时变为零，这个临界温度就是锡的正常转变点。对磁矩随温度变化的作图，我们得到一条与临界磁场随温度变化的曲线形状类似的曲线。 [英文](#)

(2) 同样的球体在无任何外磁场的情况下冷却到2.5 K，打开并立即关闭230高斯的磁场 (高于在此温度下的临界磁场)。结果在温度为2.5 K时产生的磁矩比上一实验中使用70高斯时产生的磁矩大8%，而当温度上升时磁矩不断下降，在温度上升到2.9 K时，磁矩与在以前实验中温度为2.9 K时的磁矩值相同。在温度为2.9 K ~ 4 K的范围内，得到的曲线与实验 (1) 中这个温度段的曲线重合。 [英文](#)

(3) 与上述实验类似，只是改用半径相同的空心锡球进行研究，中心的球型空心是整个球体积的一半。空心球产生的磁矩是实心球的2 ~ 3倍。 [英文](#)

在所有这些实验中，磁场是由缠绕成圆筒状的线圈产生的，圆球置于线圈的中部，实验中没有使用任何铁质材料。尽管这样可以使圆球附近的磁场相当均匀，但我们还是认为，观测到的现象可能会受到外场细微的非均匀性的影响。而即便在一个完全均匀的磁场中，冷却方法也可能影响到最终的结果。为了验证这一点，我们分别从圆球的两极和赤道位置对其进行冷却。然而这个做法并没有导致任何差异的产生，两种情况下观测到的磁矩的数量级是相同的。 [英文](#)

根据这些实验的结果，我们似乎肯定，亦如迈斯纳和奥克森费尔德所观测的，当物质成为超导体时，它们的有效磁导率会减小。另一方面，很显然在我们当前的实验条件下，磁导率并不会如电导率趋于一个无限值状况所预期的那样完全消失，或者即便磁导率完全消失，那也仅是发生在部分区域内，而不会贯穿整个超导体。 [英文](#)

最后，我们要感谢基利先生，他在我们工作的各个阶段都给予了建议和大量帮助。 [英文](#)

（ 沈乃澍 翻译；郑东宁 审稿）

The Velocity of Light

M. E. J. Gheury de Bray

There were many occasions in the early decades of the publication when *Nature* deliberately published items that were calculated to surprise and even challenge orthodox opinion. Thus the journal published in the 1930s three letters from a man called M. E. J. Gheury de Bray advocating the opinion that the velocity of light is not constant in time but that it had slowly decreased between 1924 and 1933. The possibility of a slow change in supposed “constants” of physics is now back in vogue among cosmologists, albeit so far without compelling evidence to support it. [中文](#)

IN 1927 there was published in these columns¹ a table of all the determinations of the velocity of light which I compiled from the original memoirs, together with a discussion, and I pointed out that except a pair of practically simultaneous values obtained in 1882 the final values (printed in heavy type) indicate a secular decrease of velocity. The last (and lowest) value given is $299,796 \pm 4$ km./sec. for 1926. [中文](#)

Since then, two determinations have been made: the first by Karolus and Mittelstaedt (1928) using a Kerr cell, to the terminals of which an alternating potential was applied, for interrupting periodically the luminous beam, instead of a toothed wheel². A frequency can be obtained in this way, of the order of a million per second, which can be accurately calculated, thus permitting a very short base to be used

(41.386 metre) without any loss of accuracy. The value found (mean of 755 measurements) was $299,778 \pm 20$ km./sec. The second recent determination is mentioned in *Nature* of February 3, p.169: it gives for the velocity of light in 1933 the value $299,774 \pm 1$ or 2 km./sec.

中文

The determinations of this so-called constant made during the last ten years (the most accurate of the whole series) are therefore:

1924	..	..	$299,802 \pm 30$ km./sec.
1926	..	..	$299,796 \pm 4$ km./sec.
1928	..	..	$299,778 \pm 20$ km./sec.
1933	..	..	$299,774 \pm 1$ or 2 km./sec.

中文

No physicist, looking at the above table, can but admit that the alleged constancy of the velocity of light is absolutely unsupported by observations. As a matter of fact, the above data, treated by Cauchy’s method³, give the linear law:

$$V_{\text{km./sec.}} = 299,900 - 4T_{(1900)} \text{ years.}$$

中文

When I first pointed out this fact (in 1924) it was objected that the data available were inconclusive, because the probable errors of the observations were greater than the alleged rate of change. Sir Arthur Eddington has dealt the death blow to the theory of errors⁴ and “this theory is the last surviving stronghold of those who would reject plain fact and common sense in favour of remote deductions from unverifiable guesses, having no merit other than mathematical tractability”⁵. Even “die-hards”, however, may fruitfully meditate over the 2nd and the 4th values in the above table.

中文

(133, 464; 1934)

M. E. J. Gheury de Bray: 40 Westmount Road, Eltham, S.E.9.

1. *Nature*, **120**, 603, Oct. 22, 1927.
2. *Phys. Z.*, 698-702; 165-167; 1929.
3. *Engineer*, Sept. 13, 1912.
4. *Proc. Phys. Soc.*, 271-282; 1933.
5. Dr. N. R. Campbell, *loc. cit.*, 283.

光的速度

谷瑞·德布雷

在《自然》杂志发行的前几十年中，它对于发表那些旨在抨击甚至挑战传统观点的文章是非常慎重的，但事实上它仍然发表了很多这类文章。20世纪30年代，《自然》就发表了一个名为谷瑞·德布雷的人的三篇通讯，他的观点是光速并不是永远恒定的，在1924年至1933年间光速随时间在缓慢地减小。天文学家中又掀起了这样一种风潮，即发现物理学中原以为“恒定”的事物存在缓慢变化的可能性，不过目前尚无确凿的证据证实这一观点。 [英文](#)

本专栏在1927年^[1]发表了我从原始文献中汇集的关于光速的全部测定结果的列表以及对此进行的讨论。我曾指出，除了一对几乎同时于1882年获得的数值之外，最终结果（黑体字印刷）显示出光速在不断地减少。表中所给出的最后一个（也是最小的一个）数值是1926年测得的 $299,796 \pm 4$ 千米/秒。 [英文](#)

在那以后，科学家又得到了两个测定结果：第一个来自卡罗卢斯和米特尔施泰特（1928），他们使用了克尔盒，并在其终端施加交变电压来代替齿轮，用以周期性地隔断光束^[2]。用这种方式可以精确地计算并得到每秒百万数量级的隔断频率，从而可以使用一个极短的基线（41.386米）而丝毫不损失精确性。由此而得到的光速数值（755次测量结果的平均值）为 $299,778 \pm 20$ 千米/秒。第二个近期测定结果是在2月3日出版的《自然》杂志第169页给出的，它测定于1933年，值为 $299,774 \pm 1$ （或2）千米/秒。 [英文](#)

因此，可以将最近十年中对光速这一所谓常数的测定结果（整个序列中最为精确的）排列如下：

1924	..	..	299,802 ± 30 千米 / 秒
1926	..	..	299,796 ± 4 千米 / 秒
1928	..	..	299,778 ± 20 千米 / 秒
1933	..	..	299,774 ± 1 (或 2) 千米 / 秒

英文

看过上面的表后，物理学家们不得不承认，所谓的光速恒定性显然没有得到观测结果的支持。事实上，经过柯西方法^[3]处理后，上述光速测量值与测量年份满足线性关系：

$$V_{\text{千米/秒}} = 299,900 - 4T_{20\text{世纪各年份}} \quad \text{英文}$$

我第一次指出这一事实时（1924年），有人反对说现有的数据是不确定的，因为观测中的或然误差大于所谓的变化速率。阿瑟·爱丁顿爵士曾对这一误差理论^[4]施以致命一击：“对于那些拒绝承认明确的事实与常识却喜欢从无法检验的猜测中得出间接推论的人来说，该理论是最后的生存堡垒，它除了数学便利性之外毫无优点可言”^[5]。但是，即使是“老顽固们”也可能会对上表中第2和第4个值进行一番深刻的思考。

英文

（王耀杨 翻译；张元仲 审稿）

Attempt to Detect a Neutral Particle of Small Mass

In 1930, Wolfgang Pauli hypothesized that nuclear beta decay might involve a second particle being emitted from the nucleus in addition to the electron. He pointed out that the puzzling continuous variation in energy of beta-decay electrons could be understood if a second, electrically neutral particle carries away a varying amount of energy. Fermi named the proposed particle the neutrino, and here *Nature* reports on a failed attempt by Chadwick and colleagues to detect it. If such particles do exist, they found, they must have very small mass. Indeed they do, and because they interact so weakly with other particles, neutrinos are enormous difficult to detect. This was finally achieved in 1956. Physicists later discovered that neutrinos come in three flavours. [中文](#)

CHADWICK and Lea have recently published the negative result of an experiment designed to examine the possibility that the continuous β -ray spectrum is accompanied by the emission of penetrating neutral particles (*Proc. Camb. Phil. Soc.*, **30**, Part 1). The energies of these particles might be distributed in such a way that they combine with those of the β -particles to form a constant energy of disintegration, a low energy β -particle being associated with a high energy "neutrino". A strong source of radium D + E + F (radium E gives a well-marked continuous β -ray spectrum) was placed near a high-pressure ionisation chamber and an absorption curve was taken with lead screens. The

radiation was all identified with the radium E and polonium γ -rays. If neutral particles are emitted, it is calculated that they cannot produce more than 1 ion pair in 150 kilometres path in air. A consideration of the possible nature of the particle shows that, if it exists, it must have small mass and zero magnetic moment. [中文](#)

(133, 466; 1934)

探测小质量中性粒子的尝试

1930年，沃尔夫冈·泡利猜测原子核在 β 衰变过程中除了产生电子之外还会放出第二种粒子。他指出如果这第二种电中性的粒子携带了不同大小的能量，那么令人困扰的 β 衰变过程中电子能量的连续变化就可以得到解释了。费米将这一假想的粒子命名为中微子，《自然》在这篇文章中报道了查德威克和他的同事在探测中微子方面的一次失败的尝试。他们发现如果这一粒子确实存在，它们一定具有非常小的质量。事实正是如此，而且正因为中微子与其他粒子的相互作用非常微弱，所以中微子的探测异常困难。这一探测最终于1956年获得成功。之后物理学家又发现中微子有三种味。 [英文](#)

最近，查德威克和利发表了他们实验得到的负面结果，设计该实验的目的是检验连续 β 射线谱伴随着发射出具有穿透性的中性粒子的可能性（《剑桥哲学学会会刊》，第30卷，第1部分）。上述中性粒子的能量可能是以这样的方式分布的：中性粒子能量与 β 粒子能量之和等于一个恒定的衰变能，由此把低能 β 粒子与高能“中微子”联系了起来。将一个包含镭D、镭E和镭F的强放射源（镭E可以给出很清楚的连续 β 射线谱）置于高压电离室附近，并利用铅屏来获得吸收曲线。得到的谱线与镭E的射线谱及钋的 γ 射线谱是完全一致的。经过计算可得，即使有中性粒子发射，它们也不可能在空气中150 km的路径内产生出多于1个的离子对。对这种中性粒子可能的性质考虑得到的结果是，如果它们存在的话，其质量一定很小且磁矩为零。 [英文](#)

（王耀杨 翻译；朱永生 审稿）

Developments of Television

In a theatre in the West End of London on 20 March 1934, *Nature* reports here, shareholders of Baird Television Ltd. saw and heard the chairman address them from a studio at the Crystal Palace eight miles away. The feat relied on the a newly developed large cathode-ray oscilloscope, as well as high-quality photo-cells and amplifiers capable of processing signals over a wide frequency range. Transmissions from the Crystal Palace location could broadcast television signals to the whole of Greater London. The report notes that another demonstration is planned of a method reported earlier in *Nature* by which television images of topical events might be displayed on cinema screens and home receivers within only a few seconds of having happened. 中文

AN application of science has enabled a chairman of a company to become a historic figure. At the annual general meeting of Baird Television, Ltd., held in a theatre in the west end of London on March 20, the shareholders heard and saw distinctly the chairman address them from a studio at the Crystal Palace, nearly eight miles distant. To the shareholders, and afterwards to representatives of the Press, the Baird Company arranged a programme of transmissions by radio from the Crystal Palace to enable the audience to see persons talking on various subjects, a cartoonist sketching at his easel, excerpts from popular films and “still” pictures. All these items were reproduced in the receiver with sufficient detail for an audience of more than a hundred persons to “look in”, although the receiver was devised for

use in the home rather than a theatre. The success of these demonstrations is attributed to the state of perfection of the large cathode ray oscillographs made exclusively for the Baird Co. by the research staff of a British industrial concern, the excellence of the photoelectric cells in use at the transmitting end, and the construction of amplifiers which are capable of dealing without phase distortion with a range of frequencies from 25 to 1,000,000 cycles per second. The subject matter to be televised is divided up into 180 lines (or strips) corresponding to 24 times the definition obtainable with the old 30-line apparatus. Vision is being transmitted from a dipole aerial on a wave-length of 6.0 metres, and sound on 6.25 metres. 中文

Judging from the demonstrations given last week, the Baird Company's engineers have successfully overcome interference effects due to motors, lifts and other electro-magnetic disturbances met with at these short wave-lengths. A series of experiments have been carried out to ascertain the effective range of reception, as a result of which it is claimed that the Crystal Palace transmitting station can provide an ultra-short wave high definition television service for the whole of the Greater London area, which includes a population of about eight millions. Capt. A. G. D. West, who joined the board of the Baird Company last June to direct its technical development, is to be warmly congratulated on his achievement; and the Company on the first public demonstration of the broadcasting possibilities of high-definition television. We understand that a demonstration will shortly be given of the intermediate film-method, described by Major A. G. Church in *Nature* of September 30, 1933, by means of which televised images of topical events will be thrown on screens in cinema theatres as well as on home-receivers within a few seconds of their occurrence. Another series of experiments on a new system of "scanning" invented by Mr. Baird is nearing completion. These experiments aim at securing sufficient illumination in a studio to enable "crowd" scenes to be televised directly with detailed fidelity. 中文

电视的发展

《自然》的这篇文章报道了1934年3月20日在伦敦西区一个剧院中，贝尔德电视有限公司的股东们观看并且听到董事会主席在8英里外的水晶宫演播室向他们进行的演讲。这一成就得益于最近研制出的大型阴极射线示波器、高质量的光电管和能够处理宽频率范围信号的放大器。从水晶宫输出的信号可以为整个大伦敦地区提供电视信号。这篇报道提到了《自然》先前报道的另一种计划用于电视方面的技术，该技术可以使时事新闻的电视图像在事件发生后的几秒内显示在电影院屏幕或者家用接收机上。 [英文](#)

科学的一项应用使一家公司的董事长成为了历史性的人物。3月20日，贝尔德电视有限公司的年会在伦敦西区的一个剧院内召开，会上股东们清楚地听到并看见董事长在将近8英里外的水晶宫演播室向他们发表演讲。贝尔德公司给股东们，随后给出版社代表们安排了一个节目，节目通过无线电波从水晶宫传送信号，观众们能够看到谈论着不同话题的人们、一个正在画架上素描的漫画家以及一些从流行电影和“静止的”图画上摘选的内容。所有这些内容都被细致地再现于接收机上，供100多名观众“观看”，尽管接收机原本是为在家里而不是在剧院使用设计的。这些演示的成功主要归于以下几个原因：英国一家工业公司的研究人员专门为贝尔德公司制造的大型阴极射线示波器堪称完美，在发射端使用的光电管的性能非常优秀，新造的放大器能够无相位失真地处理每秒25周到每秒100万周频率范围内的信号。通过电视播放的内容被分解成180线（或带），这样其清晰度就是以前只能分解成30线的老设备的24倍。图像从一个偶极子天线处以波长6米的信号传出，而声音则以波长6.25米的信号传出。 [英文](#)

从上周进行的演示来判断，贝尔德公司的工程师们已经成功克服了由汽车、电梯以及在这些短波长范围内的其他电磁干扰所产生的干涉效

应。另外，工程师们也进行了一系列实验来确定有效的接收范围，据称，实验结果表明水晶宫的发射台能够为拥有约800万人口的整个大伦敦地区提供超短波的高清电视服务。去年6月加入贝尔德公司董事会主管公司技术发展的韦斯特上尉一定会因其成就受到热烈的祝贺，贝尔德公司也会因首次公开演示了高清电视播送的可能性而被人们赞颂。我们可以预计，很快就会出现使用中间胶片法进行的演示。在1933年9月30日的《自然》上丘奇少校曾描述过该方法，通过这种方法，时事新闻的电视图像能够在事件发生后的几秒内显示在电影院屏幕或者家用接收机上。在贝尔德先生发明的新“扫描”系统上进行的另一系列实验也快要完成了。这些实验的目的是确保演播室有足够的照明度，以使“拥挤”的镜头能直接高保真地在电视上播放。

英文

（刘霞 翻译；赵见高 审稿）

The “Neutrino”

H. Bethe and R. Peierls

Hans Bethe and Rudolf Peierls here discuss the implications of Wolfgang Pauli’s proposal that radioactive beta decay involves a hitherto unknown particle, the neutrino. If such a particle had small mass and spin $1/2$, the continuous spread of energy of electrons emitted in beta decay would make sense, and energy and momentum conservation need not be abandoned for nuclear processes. They suggest that the neutrino is created at the moment of decay, and that a neutrino may initiate a reverse beta decay when impinging upon nuclei. However, by their estimates a neutrino should interact so weakly with other matter that observing the latter would be most unlikely. Indeed, they can see no way yet to observe a neutrino. [中文](#)

THE view has recently been put forward¹ that a neutral particle of about electronic mass, and spin $\frac{1}{2}\hbar$ (where $\hbar = h/2\pi$) exists, and that this “neutrino” is emitted together with an electron in β -decay. This assumption allows the conservation laws for energy and angular momentum to hold in nuclear physics². Both the emitted electron and neutrino could be described either (a) as having existed before in the nucleus or (b) as being created at the time of emission. In a recent paper³ Fermi has proposed a model of β -disintegration using (b) which seems to be confirmed by experiment. [中文](#)

According to (a), one should picture the neutron as being built up of a

proton, an electron and a neutrino, while if one accepts (b), the rôles of neutron and proton would be symmetrical⁴ and one would expect that positive electrons could also sometimes be created together with a neutrino in nuclear transformations. Therefore the experiments of Curie and Joliot⁵ on an artificial positive β -decay give strong support to method (b), as one can scarcely assume the existence of positive electrons in the nucleus. [中文](#)

Why, then, have positive electrons never been found in the natural β -decay? This can be explained by the fact that radioactivity usually starts with α -emission and therefore leads to nuclei the charge of which is too small compared with their weight. The artificial β -emission was found for two unstable nuclei (most probably N^{13} and P^{30}) formed by capture of an α -particle and emission of a neutron, and therefore having too high a charge for their mass. [中文](#)

A consequence of assumption (b) is that two isobares differing by 1 in atomic number can only be stable if the difference of their masses is less than the mass of electron and neutrino together. For otherwise the heavier of the two elements would disintegrate with emission of a neutrino and either a positive or negative electron. There will be only a limited region on the mass defect curve, probably at medium atomic weight, where such small differences are possible. In fact, neighbouring isobares have only been found with the mass numbers 87, 115, 121, 123, (187), (203), while isobares with atomic numbers differing by 2 are very frequent. In the first case, one of the two nuclei (Rb) is known to emit β -rays. In each of the last two cases one of the two isobares is stated to be exceedingly rare and its identification might be due to experimental error. The other three cases actually lie close together and have medium weight. A particular case of isobares are proton and neutron. Since all experimentally deduced values of the neutron mass lie between 1.0068 and 1.0078, they are certainly both stable even if the mass of the neutrino should be zero. [中文](#)

The possibility of creating neutrinos necessarily implies the existence of annihilation processes. The most interesting amongst them would be the following: a neutrino hits a nucleus and a positive or negative electron is created while the neutrino disappears and the charge of the nucleus changes by 1. [中文](#)

The cross section σ for such processes for a neutrino of given energy may be estimated from the lifetime t of β -radiating nuclei giving neutrinos of the same energy. (This estimate is in accord with Fermi's model but is more general.) Dimensionally, the connexion will be

$$\sigma = A/t$$

where A has the dimension $\text{cm}^2 \text{ sec}$. The longest length and time which can possibly be involved are $\hbar/mc$ and $\hbar/mc^2$. Therefore

$$\sigma < \frac{\hbar^3}{m^3 c^4 t}$$

For an energy of 2.3×10^6 volts, t is 3 minutes and therefore $\sigma < 10^{-44} \text{ cm}^2$ (corresponding to a penetrating power of 10^{16} km . in solid matter). It is therefore absolutely impossible to observe processes of this kind with the neutrinos created in nuclear transformations. [中文](#)

With increasing energy, σ increases (in Fermi's model³ for large energies as $(E/mc^2)^2$) but even if one assumes a very steep increase, it seems highly improbable that, even for cosmic ray energies, σ becomes large enough to allow the process to be observed. [中文](#)

If, therefore, the neutrino has no interaction with other particles besides the processes of creation and annihilation mentioned—and it is not necessary to assume interaction in order to explain the function of the neutrino in nuclear transformations—one can conclude that there is no practically possible way of observing the neutrino. [中文](#)

H. Bethe and R. Peierls: Physical Laboratory, University, Manchester, Feb. 20.

References:

1. W. Pauli, quoted repeatedly since 1931, to be published shortly in “Rapports du Septième Conseil Solvay, Brussels”, 1933.
2. C. D. Ellis and N. F. Mott, *Proc. Roy. Soc., A*, **141**, 502; 1933.
3. E. Fermi, *La Ricerca Scientifica*, **2**, No. 12; 1933.
4. This point of view was first put forward by I. Curie and F. Joliot at the Conseil Solvay, 1933.
5. I. Curie and F. Joliot, *Nature*, **133**, 201, Feb. 10, 1934.

“中微子”

贝特，佩尔斯

泡利认为放射性 β 衰变的过程中涉及了一种未知粒子——中微子，汉斯·贝特和鲁道夫·佩尔斯在这篇文章中对沃尔夫冈·泡利这一提议的含义进行了讨论。如果这种粒子质量很小且自旋为 $1/2$ ，那么 β 衰变中放出的电子能谱的连续性就是可以理解的，而且核反应过程也因此而能满足能量和动量守恒。他们认为衰变发生时产生了中微子，并且中微子冲击原子核时会引发 β 衰变的逆过程。然而，根据他们的估算，中微子与其他物质的相互作用非常弱，因而难以观测。实际上，他们当时仍然没有找到任何办法来实现对中微子的观测。

[英文](#)

最近有观点认为^[1]，存在质量和电子差不多、自旋为 $\frac{1}{2}\hbar$ ($\hbar = h/2\pi$) 的中性粒子，而这种“中微子”是在发生 β 衰变时与电子一起发射出来的。以上这个假设使得能量和角动量守恒定律在核物理中也得以成立^[2]。衰变过程中发射出来的电子和中微子均可被认为是 (α) 衰变发生前就存在于核中，或 (b) 衰变发生时创生出来的。在最近的一篇文章中^[3]，费米利用假设 (b) 提出了一种 β 衰变的模型，而这一假设似乎得到了实验的证实。

[英文](#)

按照 (a) 的解释，中子应该是由一个质子、一个电子和一个中微子组成的，而如果采纳 (b) 的解释，则中子和质子的作用就是对称的^[4]，因此在核转变中也有可能同时发射出正电子和中微子。人们不太可能接受原子核中存在正电子的观点，因此，居里和约里奥^[5]用人工正 β 衰变的实验有力地证明了 (b) 的解释是正确的。

[英文](#)

那么，为什么从未在天然 β 衰变中发现过正电子呢？这可以用以下事实进行解释：放射现象通常先出现 α 发射，从而导致核的电荷与其质

量相比很小。而人工 β 发射发现于两种不稳定核（最可能是 ^{13}N 和 ^{30}P ）的形成过程中，即吸收一个 α 粒子并发射出一个中子，因此相对其质量而言，该不稳定的核具有很高的电荷。 [英文](#)

由假设（b）可得到以下结论：原子序数相差1的两个同量异位素只有在它们的质量差小于电子和中微子的质量之和时才是稳定的。否则，两个元素中较重的一个将发生蜕变并发射出一个中微子和一个正电子（或负电子）。两个同量异位素的质量差如此之小的情况对应于质量亏损曲线上有限的区域，该区域大概位于中等原子量处。实际上，已发现的原子序数相差1的同量异位素的质量数只有87、115、121、123、（187）和（203），而原子序数相差2的同量异位素是很常见的。对应上述第一个质量数，已知两种核之一（Rb）会发射 β 射线。而对应最后两个质量数，每个质量数的两种同量异位素中的任何一种都可以说相当稀少，而且很可能是实验误差导致大家以为存在着该同量异位素。其他三个质量数实际上很接近，且都具有中等的原子量。质子和中子是同量异位素的特殊情况。由于所有实验导出的中子质量值均在1.0068和1.0078之间，所以即使中微子的质量为零，中子和质子也肯定都是稳定的。 [英文](#)

产生中微子的可能性必然意味着湮灭过程的存在。这些现象中最令人感兴趣的是以下过程：一个中微子撞击一个核后，中微子消失并产生一个正电子或负电子，核的电荷数改变了1。 [英文](#)

给定能量的中微子发生以上过程时，其散射截面 σ 可以通过放射出相同能量中微子的 β 衰变核的寿命 t 来估算。（这个估计与费米模型的结果一致，但更具有普适性。）在量纲上，以上两个物理量的关系式可写成

$$\sigma = A/t$$

式中 A 的量纲为 $\text{cm}^2\cdot\text{s}$ 。该问题可能涉及的最长长度和时间分别是 $\hbar/mc$ 和 $\hbar/mc^2$ 。因此

$$\sigma < \frac{\hbar^3}{m^3 c^4 t}$$

当能量为 2.3×10^6 电子伏、 t 为3分钟时， $\sigma < 10^{-44} \text{ cm}^2$ （相应于在固体物质中 10^{16} km 厚的穿透能力）。因此对于核转变时产生中微子的这类过程，我们绝对不可能观测到。 英文

随着能量的增加， σ 也随之增大（在费米模型^[3]中，当能量较大时，与 $(E/mc^2)^2$ 相当），但即使假定能量急剧增大，甚至是宇宙射线的能量， σ 也几乎不可能大到足以被我们观测到的程度。 英文

因此，如果中微子除了上述的产生和湮没过程外与其他粒子没有相互作用——而我们也没有必要通过假设这种相互作用的存在来解释中微子在核转变中的作用——则我们可以断言没有实际可行的观测中微子的方法。 英文

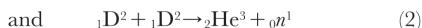
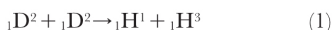
（沈乃澍 翻译；刘纯 审稿）

Disintegration of the Diplon

P. I. Dee

The recent experiments of Oliphant, Harteck and Rutherford with “diplons” (nuclei of the hydrogen isotope deuterium) suggested that they might react in pairs to form ${}^3\text{He}$ and ${}^3\text{H}$. A colleague at the Cavendish Laboratory, Philip Ivor Dee, here reports partial confirmation from cloud-chamber experiments. The nuclear reaction of two deuterium nuclei is one of the most basic in nuclear physics, featuring in the fusion processes in the Sun. [中文](#)

IT has been shown by Oliphant, Harteck and Lord Rutherford in a recent letter¹ that the bombardment by high-velocity diplons of compounds containing diplogen gives rise to three groups of particles—two groups of equal numbers of singly-charged particles of ranges 14.3 cm. and 1.6 cm., together with neutrons of maximum energy of about three million volts. They suggest as possible explanations of these results the reactions:



an atom of ${}_1\text{H}^3$ of 1.6 cm. range and a proton of 14.3 cm. range satisfying the momentum relations in reaction (1). In this reaction it is to be expected that the proton and the isotope of hydrogen of mass 3 would recoil in opposite directions, except for a small correction due to the momentum of the captured diplon. The cloud track method is extremely suitable for an examination of this possibility, and I have

recently taken expansion chamber photographs of the disintegration particles resulting from the bombardment of a target of “heavy” ammonium sulphate with dipions, to see if further information can be obtained. 中文

The first set of experiments was made with a thin target contained in an evacuated tube at the centre of the chamber. Two opposite sides of the end of this tube were closed with mica windows of 6.3 mm. and 11.4 cm. stopping power respectively. The chamber was filled with a suitable mixture of helium and air to increase the lengths of the tracks of the short particles. Under these conditions, the particles of 14.3 cm. range emerging through the thick window and the particles of 1.6 cm. range emerging through the thin window end in the chamber and the usual reprojection permits precise determination as to whether the two tracks are co-planar and of the ranges. Owing to the fine structure of the grid supporting the thin window the efficiency of collection of pairs cannot be high; also the companion to a 14.3 cm. particle passing through the thin window would not be able to pass through the opposite thick window. In spite of these difficulties, opposite pairs of tracks of about 14.3 cm. and 1.6 cm. range are observed with far greater frequency than could be attributed to chance. The photograph reproduced as Fig. 1 is a fortunate example, the short track on the right being due to the new hydrogen isotope of mass 3. Detailed measurements of the lengths of the tracks and the angles between them are being made and will be published later. 中文

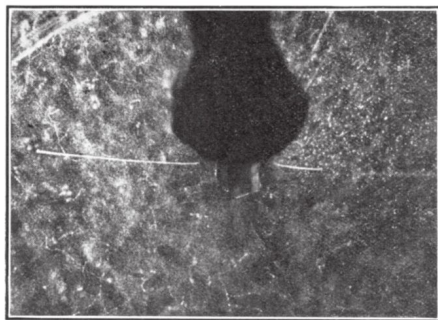


Fig. 1 中文

To investigate the neutron emission, a second series of experiments has been made in which a target of the same material contained in a lead tube of 3 mm. wall thickness was bombarded in the same manner, the chamber being filled with a mixture of 50 percent helium in air. Under these conditions, thirty-one recoil tracks originating in the gas have been photographed. Assuming that these are due to impacts with neutrons, the latter appear to constitute an approximately homogeneous group of maximum energy of about 1.8 million volts. This energy appears to be in fair agreement with reaction (2) on substitution of the mass of ${}^2\text{He}^3$, which can be estimated from consideration of the energies of the short-range products resulting from the transformation of ${}^3\text{Li}^6$ by protons^{2,3,4}. The ${}^2\text{He}^3$ group of reaction (2) with a possible range of about 5 mm. would not pass through the thinnest window used in these experiments, but special arrangements are being made to search for them in an expansion chamber. [中文](#)

These experiments are the first to be made with a new discharge tube constructed following a design due to Dr. Oliphant. I should like to acknowledge the much valuable advice which Dr. Oliphant has always so readily given me in the course of construction of this tube. I am also indebted to him for preparing the diplogen targets used in these experiments. [中文](#)

(133, 564; 1934)

P. I. Dee: Cavendish Laboratory, Cambridge.

References:

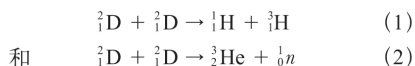
1. *Nature*, **133**, 413, March 17, 1934.
2. *Proc. Roy. Soc., A*, **141**, 722; 1933.
3. *Nature*, **132**, 818, Nov. 25, 1933.
4. *Nature*. **133**, 377, March 10, 1934.

氘核的蜕变

迪伊

奥利芬特、哈特克和卢瑟福关于“氘核”（氢的同位素氘的原子核）的新近实验表明，它们可以成对发生反应生成 ${}^3\text{He}$ 和 ${}^3\text{H}$ 。这篇文章中卡文迪什实验室的一位同事菲利普·艾弗·迪伊报道了来自云室实验的部分证据。两个氘核间的反应是核物理学中最基本的反应之一，它在太阳的核聚变过程中起着重要的作用。 [英文](#)

在最近的一篇通讯^[1]中，奥利芬特、哈特克和卢瑟福勋爵曾指出，用高速的氘核轰击含有重氢的化合物，可以产生三组粒子——其中两组射程分别为14.3厘米和1.6厘米的同等数目的单电荷粒子，以及一组最大能量约为3兆电子伏的中子。对于这些结果，他们提出下列反应作为可能的解释：



其中射程为1.6厘米的 ${}^3_1\text{H}$ 原子和射程为14.3厘米的质子就能满足反应式（1）中的动量关系。在这个反应中除了因俘获氘核的动量而做了一个小修正外，可以预期质子和质量数为3的氢同位素原子会向相反的方向反冲。采用云室径迹法来检验这一可能性是非常合适的。最近，为了考察能否获取更进一步的信息，我拍摄了一些用氘核轰击硫酸“重”铵靶而产生蜕变粒子的膨胀云室照片。 [英文](#)

第一组实验把一个薄靶置于云室中心的真空管中。管的两端用具有阻断功能分别为6.3毫米和11.4厘米的云母窗封闭。云室充有适当比例的氦和空气的混合物以增加短径迹粒子的径迹长度。在这些条件下，射程为14.3厘米的粒子从真空管的厚窗中穿出，射程为1.6厘米的粒子则从另

一端的薄窗中穿出并进入云室，而通常出现的二次投影可以精确测定粒子的射程以及其径迹是否共面。由于支撑薄窗的栅格的精细结构，粒子对的收集效率不可能高；另外，若射程为14.3厘米的粒子从薄窗中穿出，那么射程为1.6厘米的粒子就不能从对面的厚窗中穿出了。尽管存在这些困难，但我们观测到射程约为14.3厘米和1.6厘米的反向径迹对的频率远高于由于随机事件所导致的频率。图1这样的复印照片是一个幸运的例子，其中位于右方的短径迹是由质量数为3的氢的新同位素产生的。这些径迹的长度以及它们之间的夹角已被详细测量，稍后就会发表。

英文

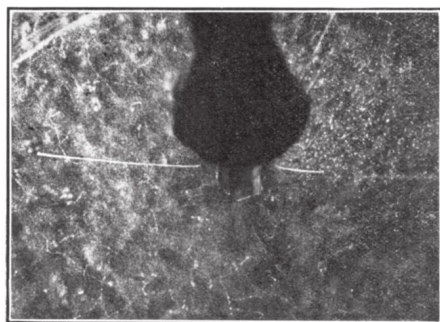


图1 英文

为了研究中子发射，我们进行了同系列的第二组实验，首先，云室中充入气体混合物为含氦量50%的空气，用相同材料的靶置于3毫米厚的铅管中并以相同的方式进行轰击。在这样的条件下，我们拍摄到了31条在气体中产生的反冲径迹。假定这些径迹是由于中子碰撞产生的，那么后者似乎构成一个最大能量约为1.8兆电子伏的近似单能峰。该能量似乎与反应式（2）中以 ^3He 的质量代入获得的能量值相当，这个质量可以根据由质子引起 ^6Li 蜕变产生的短射程产物的能量来估算[2,3,4]。反应式（2）产生的 ^3He 粒子群可能的射程约为5毫米，因此不能穿过这些实验中使用的最薄窗，但是我们正在制造一个特殊的实验装置以便能够在膨胀云室中找到它们。

英文

我们的这些实验第一次使用了根据奥利芬特博士设计而制造出的新放电管。我还要感谢奥利芬特博士在我们制造放电管期间总是不厌其烦地给我们提供非常有建设性的建议。此外，我也很感激他在为上述实验准备氦靶时所提供的帮助。

英文

(王耀杨 翻译；张焕乔 审稿)

Commercial Production of Heavy Water

A plant of Imperial Chemical Industries, *Nature* here reports, has begun commercial production of heavy water, producing as much as 5 grams per day with a purity of 30% (pure heavy water was refined at a later date). The plant uses electrolytic method, inspired by Harold Urey and Edward Washburn's discovery that the concentration of deuterium increases in water undergoing electrolysis. The company believes it will be able to supply all heavy water required for commercial purposes in the near future. Production of heavy water became a major focus of nations in the Second World War, given its potential use in nuclear reactors. [中文](#)

THE recently discovered "heavy water", which has created so much interest in popular as well as scientific circles, is to be produced commercially in England. Plant has been developed at the Billingham works of Imperial Chemical Industries, Ltd., which is capable of producing a continuous supply of heavy water of approximately 30 percent purity at the rate of 5 gm. per day, while approximately pure "heavy water" will be produced at a somewhat later date. I.C.I. anticipate that they will be able to meet any commercial demand that may arise. Urey and Washburn, in the United States, discovered that the residual water in old electrolytic cells contained a larger proportion of heavy hydrogen than the normal. It was further found that by continued electrolysis, the concentration of the "heavy water" was enriched, ordinary light hydrogen being given off preferentially,

and “heavy water” accumulating. This gave the key to a successful method of preparing “heavy water” in quantity, and the electrolytic method is the one in use at Billingham. Large-scale production of “heavy water” is only possible where exceptional resources of power and raw materials exist together. At Billingham, not only ordinary hydrogen in large quantities, but also residues in which “heavy water” has accumulated, are readily available. These resources, together with cheap power and convenient research facilities, make Billingham a logical centre for the large-scale production of the new compound. Since its discovery in the United States, its probable uses are becoming more evident, and it is eloquent testimony to the vitality of British chemical technique that in so short a space of time it should have been translated from a scientific curiosity to a marketable commodity.

中文

(133, 604; 1934)

重水的商业化生产

《自然》杂志在这篇文章中报道了帝国化学工业公司的一个工厂开始了重水的商业化生产，他们每天生产5克纯度为30%的重水（后来才精炼得到纯的重水）。哈罗德·尤里和爱德华·沃什伯恩发现重氢在水中的浓度会随着电解的进行而升高，受此启发，这个工厂使用电解的方法生产重水。该公司相信在不远的将来他们有能力满足所有对商业用重水的需求。由于其在核反应堆中的潜在应用价值，重水的生产成了第二次世界大战期间各国关注的焦点。 [英文](#)

最近发现的“重水”引起了公众及科学界极大的兴趣，并即将在英格兰进行商业化生产。帝国化学工业有限公司（简称ICI）已经在比林罕厂区建立了厂房，该厂可以以每天5克的速率持续供给纯度大约为30%的重水，不久以后将会生产接近纯净的“重水”。ICI估计他们将可以满足任何商业需求。美国的尤里和沃什伯恩发现，在旧电解池中剩余的水比一般的水含有更高比例的重氢。他们进一步发现，通过连续电解可以提高“重水”的浓度，普通的轻氢会被选择性地除去而使“重水”得到累积。这个发现为成功地进行大规模的“重水”制备提供了关键思路，而比林罕的工厂使用的正是电解的方法。只有在优越的动力和原材料同时满足的情况下才有可能大量生产“重水”。在比林罕，不仅普通氢原料充足，而且有其中累积了“重水”的残液便于利用。这些资源与廉价的动力以及方便的研究设备，使比林罕自然而然成为一个大量生产新化合物的中心。自“重水”在美国发现以来，其可能的应用价值日益明显，这也是英国化学工业技术具有生命力的有力明证，即：在非常短的时间内，重水将从科学珍品转变为具有市场价值的商品。 [英文](#)

（沈乃澂 翻译；李芝芬 审稿）

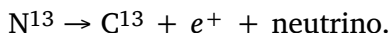
The Neutrino

H. Bethe and R. Peierls

Bethe and Peierls again write on the perplexing matter of the neutrino. It seems very unlikely, they note, that this particle would create any detectable ionisation after emerging from a nucleus. Nevertheless, its existence might still be demonstrated experimentally. One way, they suggest, would be to measure the recoil of a nucleus during beta decay. Though this energy in natural beta decays would be too small, it could be much bigger in artificial decays, for example of ^{13}N . If the neutrino hypothesis were correct, its existence would be evident from the missing energy or momentum in individual decays. Although this was not how the neutrino's existence would ultimately be demonstrated, the suggestion showed that doing so was not considered hopeless. [中文](#)

ALTHOUGH it seems very unlikely that neutrinos, after having been emitted in a nuclear process, give rise to any detectable ionisation¹, we would like to point out that it is not impossible in principle to decide experimentally whether they exist. [中文](#)

One possible experiment would be to check the energy balance for the artificial β -decay. Take, for example, the process



One can safely assume that if the positive electron is emitted with the greatest possible energy, the kinetic energy of the neutrino will just be zero. The balance of energy in this case will therefore determine the mass of the neutrino. For this purpose one would have to know the mass defects of B^{10} , C^{13} and the neutron*, the kinetic energy of the α -particles and the neutrons and the upper limit of the spectrum of the emitted positive electrons. [中文](#)

A second way of deciding the question would be to observe the recoil of the nucleus in β -decay. With natural β -rays this is in practice impossible because the recoil energy is too small, but the nuclei involved in artificial β -decay are much lighter. The kinetic energy of recoil of a disintegrating N^{13} nucleus would be of the order of some hundreds of volts if there were no neutrinos. If the neutrino hypothesis is correct, there would be a defect of momentum which would be uniquely connected with the lack of observable energy in each individual process. [中文](#)

In addition to the nuclear processes mentioned in our previous communication, it may also be expected that a nucleus catches one of its orbital electrons, decreases by one in atomic number, and emits a neutrino. (A corresponding process with increase in atomic number is not possible because of the absence of positive electrons.) This process further limits the possible mass differences between stable neighbouring isobares, and particularly between neutron and proton. If the hydrogen atom is to be stable, we must have (for the masses):

$$\text{Protom} + \text{electron} < \text{neutron} + \text{neutrino}.$$

[中文](#)

The probability of such a process is less than that of a process involving emission only, the energy of the neutrino being the same. The reason is that the momentum of the electron, which enters in the third power, is about a hundred times smaller. But even for a surplus

energy of 10^5 volts, the life-period of hydrogen would be only 10^{10} years, which seems incompatible with experimental facts. If therefore the neutrino is not heavier than the electron, the neutron must be at least as heavy as the proton. [中文](#)

(**133**, 689-690; 1934)

H. Bethe and R. Peierls: Physical Laboratory, University, Manchester, April 1.

Reference:

1. H. Bethe and R. Peierls, *Nature*, **133**, 532, April 7, 1934.

* The accuracy with which the mass of the neutron can be determined at present is, however, far from being sufficient for this purpose.

中微子

贝特，佩尔斯

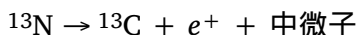
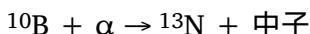
贝特和佩尔斯又一次描述了中微子令人困扰的一面。他们注意到，这种粒子从原子核中出现之后，似乎不可能引起任何可观测的电离过程。然而，中微子的存在仍需要实验的验证。他们提出的一个方法是，测量原子核在 β 衰变过程中的反冲能。尽管天然 β 衰变中的核反冲能量很小，但在人工衰变过程中这个能量可以大得多，比如 ^{13}N 核的衰变。如果中微子假说是正确的，那么各种衰变过程中的能量和动量缺失就是它存在的证据。尽管并不能通过这一方法最终证明中微子的存在，但他们的方法表明验证这点也并不是毫无希望的。

[英文](#)

虽然核转变过程中发射出来的中微子似乎不可能给出任何可观测的电离效应^[1]，但我们要指出的是，原则上用实验来判断它们是否存在还是可能的。

[英文](#)

一个可能的实验是检验人工 β 衰变前后能量是否守恒。例如下列实验过程：



我们完全可以假设，如果正电子是以最大可能的能量发射的，则中微子的动能将是零。这种情况下，根据能量守恒可以确定中微子的质量。为此，我们还必须知道 ^{10}B 、 ^{13}C 和中子*的质量亏损， α 粒子和中子的动能以及发射正电子谱的上限。

[英文](#)

判定中微子是否存在的第二种方法是观测 β 衰变中核的反冲能。用

天然 β 衰变实际上是不可能实现这一目的的，因为反冲能量太小了，但是人工 β 衰变中所涉及的核要轻得多。如果不存在中微子， ^{13}N 核发生蜕变时的反冲动能将是几百电子伏的量级。而如果确实存在中微子，则每个独立过程中都将出现与可观测到的能量亏损唯一相关的动量亏损。

英文

除了我们以前文章中提到的核转变过程外，我们还认为核可能会捕获核外的一个轨道电子，从而原子序数减小1并发射出一个中微子。

（与之对应的原子序数增加的过程是不可能的，因为不存在正电子。）这个过程进一步限制了稳定的相邻同量异位素之间，特别是质子与中子之间可能的质量差。如果氢原子是稳定的，则必须满足（对其质量而言）：

$$\text{质子} + \text{电子} < \text{中子} + \text{中微子}$$

英文

如果中微子的能量是相同的，则发生以上过程的概率小于只有发射的 β 衰变的概率。理由是以三次方形式出现的电子动量小了百倍。但即使多赋予电子 10^5 电子伏的能量，氢的寿命也仅为 10^{10} 年，这似乎与实验事实相矛盾。因此，如果中微子并不比电子重的话，则中子至少应与质子同样重。

英文

（沈乃澂 翻译；刘纯 审稿）

* 目前可以确定中子的质量，但远未达到所需的精确度。

Liquefaction of Helium by an Adiabatic Method without Pre-cooling with Liquid Hydrogen

P. Kapitza

Russian physicist Pyotr Kapitza reports on a new technique for liquefying hydrogen and helium, developed by himself and colleagues in Cambridge. These substances, so useful for modern physics research, were still being liquefied by methods dating from the beginning of the century. But his group had now developed a method based primarily on adiabatic expansion, in which no heat is lost or gained in the process. Their design eliminated the need for lubricants capable of working at such low temperatures, and could produce up to one litre per hour. The method would soon provide abundant supplies of liquid helium and hydrogen for low-temperature physics. [中文](#)

THE methods for the continuous liquefaction of hydrogen and helium at present in use are essentially the same as those originally used by Dewar and Kamerlingh Onnes when these gases were first liquefied. These methods are based on the use of the Joule–Thomson effect, combined with a regenerating heat exchange after the gas has been cooled below its conversion temperature by liquid air or hydrogen. Since these processes are essentially nonreversible, the efficiency of the method is very low: for example, Meissner¹ calculates

that to produce liquid helium, one hundred times more power is required than if the process could be done reversibly. The advantages to be gained by using adiabatic expansion for the cooling of liquefying gases have long been realised, but owing to technical difficulties this method has only been used up to the present to liquefy small amounts of gas by a single expansion. Thus in 1895, Olszewski was the first to obtain a fog of liquid hydrogen drops by a sudden expansion of compressed hydrogen. Recently, Simon² has produced appreciable quantities of liquid helium also by a sudden expansion of highly compressed helium. [中文](#)

The technical difficulties in constructing an apparatus for continuous liquefaction by adiabatic expansion lie chiefly in the designing of a cooling expansion engine which will work at low temperatures. Two principal types of expansion engine can be considered. The first is a turbine, but this involves a number of technical difficulties which have not yet been overcome. The second type of machine is a reciprocating moving piston expansion engine; this also involves great difficulties, chiefly arising from the difficulty of finding a lubricant which will make the piston tight in the cylinder and retain its lubricating properties at the very low temperatures. Claude, however, managed to make such an expansion engine which would work at the temperature of liquid air by using the liquefied gas as the lubricant. This method, however, does not appear to be practicable for liquefying helium and hydrogen. [中文](#)

During the last year, in our laboratory we have been working on the development of a reciprocating expansion engine working on a different principle which does not require any lubrication of the piston at all, and which will work at any temperature. The main feature of the method is that the piston is loosely fitted in the cylinder with a definite clearance, and when the gas is introduced into the cylinder at high pressure, it is allowed to escape freely through the gap between

the cylinder and the piston. The expansion engine is arranged in such a way that the piston moves very rapidly on the expanding stroke, and the expansion takes place in such a small fraction of a second that the amount of gas escaping through the gap is very small and does not appreciably affect the efficiency of the machine. 中文

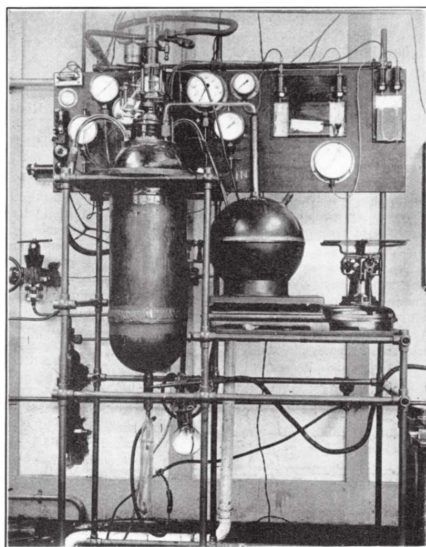


Fig. 1. Helium liquefaction apparatus at the Royal Society Mond Laboratory. 中文

The principal difficulty in constructing such a machine was concerned with the valves in the expansion engine, which had to let in a considerable amount of gas in a small fraction of a second. Another difficulty was to find metals with the necessary mechanical properties for use at these low temperatures. All these difficulties have now been successfully overcome, and the liquefier is shown in the accompanying photograph (Fig. 1). The expansion engine is placed in the middle of the evacuated cylindrical copper casing, the dimensions of which are 75 cm. long and 25 cm. diameter. The casing also contains heat-exchanging spirals and a container of liquid air for the preliminary cooling of the helium. Helium is compressed to 25–30 atmospheres and is first cooled to the temperature of liquid air and then cooled by the expansion engine and regenerating spiral to about 8°K .; the final liquefaction is produced by making use of the Joule-Thomson effect.

This combination proves to be the most efficient method of liquefaction. The liquid helium is drawn off from the bottom of the liquefier by means of a tap. [中文](#)

Following the preliminary cooling to the temperature of liquid nitrogen, the liquefier starts after 45 minutes to liquefy helium at a rate of 1 litre per hour, consuming about 3 litres of liquid air per litre of liquid helium. This output we hope will shortly be increased, but even now it compares very favourably with the original method of making liquid helium, in which, according to Meissner (*loc. cit.*), the consumption is 6 litres of liquid air plus 5 litres of liquid hydrogen per litre of liquid helium. It is also evidently a considerable advantage to be able to dispense with liquid hydrogen as a preliminary cooling agent. Theoretically it would be possible in our case also to dispense with liquid air, but the size of the liquefier would then be impracticably large. Using liquid hydrogen as a cooling agent, the output of the liquefier could be increased about six times. [中文](#)

The same liquefier has also been used for liquefying hydrogen, which was passed through a special circuit under a pressure of a few atmospheres. [中文](#)

A detailed description of the apparatus will shortly be published elsewhere. [中文](#)

(133, 708-709; 1934)

P. Kapitza: F.R.S., Royal Society Mond Laboratory, Cambridge.

References:

1. "Handbuch der Physik." Geiger and Scheel, vol. 11, p. 328.
2. *Z. Phys.*, **81**, 816; 1933.

无液氢预冷的绝热法氦液化

卡皮查

俄罗斯物理学家彼得·卡皮查报道了一种将氢和氦液化的新技术，这一技术是由他和他在剑桥的同事们共同研发的。这些对现代物理学研究非常有用的物质，仍在使用20世纪初的液化技术。卡皮查的研究小组发展出了一种主要基于绝热膨胀的技术，在绝热膨胀过程中，既没有热量失去也没有热量获得。他们的设计无须使用必须能够在同样的低温下工作的润滑剂，而且可以将产量提升至每小时1升。这种方法很快就为低温物理实验提供了充足的液氢和液氦。

英文

目前所用的氢和氦连续液化方法，本质上与杜瓦和卡默林·昂内斯首次将这些气体液化时所用的方法相同。这些方法是基于焦耳-汤姆孙效应，并结合了再生式热交换，即利用气体被液态空气或液氢冷却到低于其转变温度后的部分返回气体实现的。由于这些过程本质上是不可逆的，因此这种方法的效率非常低：例如，迈斯纳^[1]对这一过程的液氢产生效率进行了计算，发现它所需要的能量比可逆过程高出一百倍以上。人们很早以前就已了解到用绝热膨胀的方法对被液化气体进行冷却的优势，但由于技术上的困难，这类方法至今仅用于通过单次膨胀实现少量气体的液化。1895年，奥尔谢夫斯基通过将压缩的氢突然膨胀的方法首次获得了液氢滴雾。最近，西蒙^[2]同样采用将高度压缩的氦突然膨胀的方法，产生了数量可观的液氦。

英文

制造通过绝热膨胀实现连续液化的设备，其技术难点主要在于对低温下工作的冷却膨胀机的设计。有两种主要的膨胀机类型可以考虑。第一类是涡轮机，但这涉及许多尚未攻克的技术难题。第二类机器是往复运动的活塞膨胀机；这也有很大的困难，主要是难以找到一种可以使活

塞紧密贴近汽缸，同时在极低温下保持润滑的润滑剂。但克劳德通过采用被液化的气体作为润滑剂的方法，设法使这一类型的膨胀机可以在液态空气的温度下工作。不过，这个方法对于氢和氦的液化似乎并不可行。 英文

去年，我们实验室在研制一种基于不同原理工作的往复式膨胀机，它完全不需要对活塞进行任何润滑，并可以在任何温度下工作。这种方法的主要特征是，活塞宽松地装配于气缸中，之间留有一定的空隙，当气体在高压下被引入气缸时，允许其通过气缸与活塞之间的间隙自由地逸出。膨胀机被设计成在膨胀冲程内活塞运动得非常快，并且膨胀过程发生在远小于1秒的时间内，使得通过间隙逸出的气体量很少，不会明显地影响机器的效率。 英文

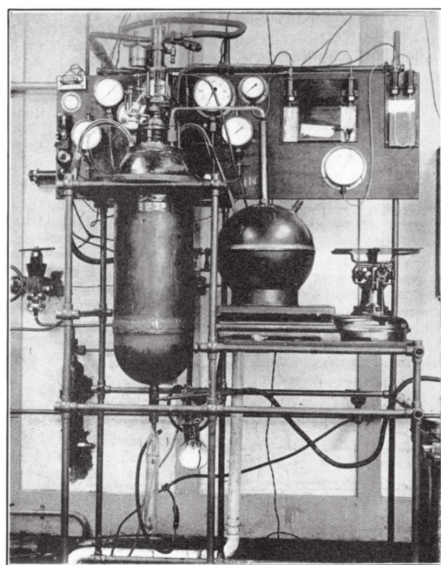


图1.皇家学会蒙德实验室的氮液化装置 英文

制造这种机器所遇到的主要困难是膨胀机中的阀门，它必须在远小于1秒的时间内让大量的气体进入。另一个困难是寻找在这样低的温度下具有必要力学性能的一些金属。现在所有这些难题均已成功得到解决，液化器如照片（图1）中所示。膨胀机置于抽空的圆筒形铜制壳体的中间，其尺寸为长75 cm，直径25 cm。壳体内还包含热交换螺旋管，以及用于盛预冷氮的液空的容器。氮被压缩到25~30个大气压，并先被冷却到液态空气的温度，然后用膨胀机和再生式热交换螺旋管冷却

到8 K；最终的液化是利用焦耳-汤姆孙效应实现的。这种组合方式被证明是最有效的液化方法。液氢通过阀门从液化器的底部抽取出来。

英文

在预冷到液氮温度之后，液化器在45分钟后开始以每小时1升的速率液化氢，每升液氢约消耗3升液态空气。我们期望产量很快会得到提高，不过即使是现在这样的水平，与原有的生产液氢的方法相比也是非常有优势的，按迈斯纳（在上引文中）的计算，原有方法每制备1升液氢要消耗6升液态空气加5升液氢。显然，新方法不使用液氢作预冷剂是一个非常大的优势。理论上讲，我们的方法中也可以不用液态空气，不过这样会使液化器的尺寸大得无法实现。如果用液氢作为冷却剂，液化器的产量大约可以增加为原来的六倍。

英文

同样的液化器也已被用于氢的液化，其中氢气会在几个大气压下通过一个特殊管路。

英文

有关装置的详细描述将于近期发表在其他文章中。

英文

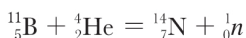
（沈乃澂 翻译；陶宏杰 审稿）

Mass of the Neutron

I. Curie and F. Joliot

James Chadwick had estimated the neutron mass by analysing a reaction in which an alpha particle stimulates the transformation of boron into nitrogen with emission of a neutron. His calculations required the experimental values for the masses of several nuclei. Here wife-and-husband physicists Irène Curie and Frédéric Joliot report a more accurate and higher value for the neutron mass by examining other reactions, and without using any nuclear mass other than that of the proton. This higher value suggested that one might interpret nuclear beta decays as being triggered by the decay of a neutron into a proton within the nucleus, with the ejection of an electron and a neutrino, which today remains the modern view. [中文](#)

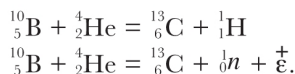
THE mass of the neutron has been calculated by Chadwick on the assumption that the neutrons of boron are emitted by the isotope $^{11}_{5}\text{B}$, according to the nuclear reaction



[中文](#)

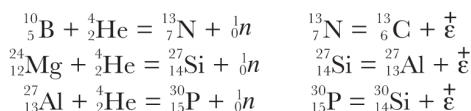
Using the exact masses of $^{11}_{5}\text{B}$, ^4_2He and $^{14}_7\text{N}$ and the maximum energy of the neutron excited by the α -rays of polonium, one may calculate for the neutron a mass 1.0068 (taking $^{16}\text{O} = 16$).¹ [中文](#)

We have suggested² that the emission of the neutron of boron is due to the isotope $^{10}_5\text{B}$ and not to $^{11}_5\text{B}$. The nucleus $^{10}_5\text{B}$ can suffer two kinds of transmutation under the action of the α -particles of polonium, one with the emission of a proton, one with the emission of a neutron and a positive electron, according to the equations:



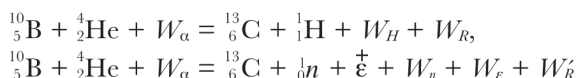
中文

Our latest experiments on the creation of new radio-elements have confirmed our interpretation of the transmutation of boron. Similar reactions are observed with the nucleus $^{27}_{13}\text{Al}$ and with $^{24}_{12}\text{Mg}$. The reactions can be divided in two steps:



$^{13}_7\text{N}$, $^{27}_{14}\text{Si}$, $^{30}_{15}\text{P}$ being unstable nuclei that disintegrate with the emission of positrons. 中文

The complete reactions, with the masses and energy of all the particles are, for the two modes of transmutation of boron:



where W_α , W_H , W_n , W_ϵ , W_R , W'_R are the energies of the α -particle and the corresponding energies of the ejected particles and of the recoil atoms in the reactions. Subtracting the first of these equations from the second gives:

$$^1_0n = \text{mass of proton} - \text{mass of positron} + Q,$$

where $Q = W_H + W_R - W_n - W'_R - W_\epsilon$. 中文

One gets exactly the same equation using the transmutations of aluminium and magnesium. [中文](#)

Thus these equations enable us to calculate the mass of neutron without using the exact masses of any nucleus, except the proton.

[中文](#)

According to our most recent measurements, the positrons emitted by the new radio-elements form a continuous spectrum of maximum energy 1.5×10^6 e.v. for $^{13}_{7}\text{N}$, 3×10^6 e.v. for $^{30}_{15}\text{P}$ and approximately 1.5×10^6 e.v. for $^{27}_{14}\text{Si}$. The emission of positrons is probably accompanied by the emission of neutrinos, but if the positrons have their maximum energy, the neutrinos will have a very small energy; the most recent hypotheses on the nature of this particle admits of a mass which is zero, or very small. So we need not take this particle into account in the calculations. The energy of the recoil atom in the disintegration with emission of a positron is negligible. [中文](#)

For the irradiation with the α -rays of polonium we have the following numerical values for the energies (expressed in 10^6 e.v.). One gets for the mass of neutron three values: 1.0098, 1.0092, 1.0089. These values agree approximately. Yet the first, deduced from boron, is the most precise. The energies of the neutrons of aluminium and magnesium and the energy of the positrons of magnesium are not well known. [中文](#)

	W_H	W_R	W_n	W'_R	W_ϵ	Q (10^6 e.v.)	Q in units of mass
B	8.05	0.23	3.3	0.59	1.5	+2.89	0.0031
Al	7.56	0.11	2	0.33	3.0	+2.34	0.0025
Mg	4.82*	0.21	1	0.48	1.5	+2.05	0.0022

* The maximum energy possible for the positrons does not correspond to a group effectively observed, but has been deduced by F. Perrin from the experiments of Bothe and Klarman, by the consideration of the energy balance relative to the groups of protons. [中文](#)

From considerations on the stability of the nucleus ^9_4Be , the mass of

the neutron should have a minimum value 1.0107. But an error of 0.001 in the determination of the mass of Be seems quite possible.

[中文](#)

We may adopt for the mass of the neutron a value 1.010, in which the error probably does not exceed 0.0005. [中文](#)

With the mass 1.010 for the neutron, the maximum energy of the neutron ejected from beryllium by α -particles from polonium should be about 9×10^6 e.v. The emission of slow neutrons when lithium is bombarded with α -particles from polonium, according to the reaction ${}^7_3\text{Li} + {}^4_2\text{He} = {}^{10}_5\text{B} + {}^1_0n$, cannot be explained unless the mass adopted for ${}^{10}_5\text{B}$ is too great, namely, by about 0.003. [中文](#)

If atomic nuclei contain only protons and neutrons, then the β -emission might be the consequence of the transformation of a neutron into a proton inside the nucleus, with the ejection of the negative electron and a neutrino, as has been suggested by several authors. The inverse processes would also be possible: transformation of a proton into a neutron with the ejection of a positron and a neutrino. [中文](#)

With the mass 1.010 for the neutron, the energy liberated in the transformation $\text{neutron} \rightarrow \text{proton} + \bar{\epsilon}$ is 2.1×10^6 e.v.; the energy absorbed in the transformation $\text{proton} \rightarrow \text{neutron} + \epsilon^+$ is 3.1×10^6 e.v. [中文](#)

(133, 721; 1934)

I. Curie and F. Joliot: Institut du Radium, Paris, 5.

References:

1. Chadwick, *Proc. Roy. Soc.*, **136**, 692; 1932.
2. I. Curie and F. Joliot, *C.R.*, **197**, 237; 1933.

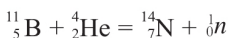
中子的质量

居里，约里奥

詹姆斯·查德威克通过分析 α 粒子引发的硼转变为氮并放出一个中子的反应，估算出了中子的质量。他的计算用到了几种原子核质量的实验值。在这篇文章中，物理学家弗雷德里克·约里奥和伊雷娜·居里夫妇通过对其他反应的研究给出了一个数值更为精确并且较大的中子质量值，并且他们的计算仅使用了质子的质量而没有用到任何其他原子核的质量。根据这一较大的中子质量数值，我们可以推测原子核的 β 衰变是由原子核中一个中子衰变为一个质子所引发的，同时放射出一个电子和一个中微子，这一观点一直沿用至今。

英文

查德威克计算了中子的质量。在计算中，他假设硼放出的中子是由同位素 ^{11}B 放出的，对应于核反应：

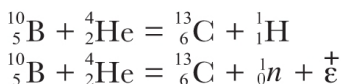


英文

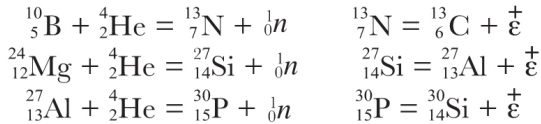
利用 $^{11}_5\text{B}$ 、 ^4_2He 和 $^{14}_7\text{N}$ 的精确质量，以及钋放射出的 α 射线所激发出的中子最大能量，可以计算出中子的质量是1.0068（取 $^{16}\text{O} = 16$ ）^[1]。

英文

但我们认为^[2]，放射出中子的是同位素 $^{10}_5\text{B}$ ，而不是 $^{11}_5\text{B}$ 。 $^{10}_5\text{B}$ 的原子核在钋放射出的 α 粒子的作用下，可以发生两种嬗变，其中一种放射出一个质子，另一种放射出一个中子和一个正电子，核反应方程分别为：



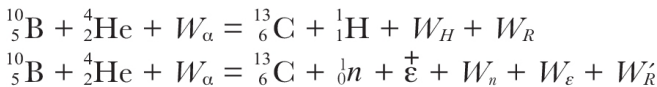
最近我们关于产生新的放射性元素的实验证实了我们对硼嬗变的解释。在 $^{27}_{13}\text{Al}$ 和 $^{27}_{12}\text{Mg}$ 中也观察到了类似的反应。反应可以分成两步：



其中， $^{13}_7\text{N}$ 、 $^{27}_{14}\text{Si}$ 、 $^{30}_{15}\text{P}$ 是不稳定的原子核，它们会发生衰变，同时放出正电子。

英文

硼嬗变的两种模式的完整的反应方程式如下，其中包含了所有粒子的能量和质量：



其中， W_α 、 W_H 、 W_n 、 W_ϵ 、 W_R 、 W'_R 分别是反应中 α 粒子的能量、放出粒子的相应能量，以及反冲原子的相应能量。用第二个反应方程式减去第一个反应方程式，可以得到：

$${}^1_0n = \text{质子的质量} - \text{正电子的质量} + Q,$$

其中， $Q = W_H + W_R - W_n - W'_R - W_\epsilon$ 。

英文

利用铝和镁的嬗变反应方程式，也可以得到完全相同的方程。

英文

这样，我们不必用到除质子以外的其他任何原子核的质量，就可以计算出中子的质量。

英文

根据我们最近的测量，新形成的放射性元素放出的正电子的能量分布为连续谱，对 $^{13}_7\text{N}$ 、 $^{30}_{15}\text{P}$ 和 $^{27}_{14}\text{Si}$ 而言，连续谱的最大能量分别是： 1.5×10^6 eV、 3×10^6 eV和大约 1.5×10^6 eV。放出正电子时大多伴随着中微子的放出，但是如果正电子有其最大能量，那么中微子的能量将非

常小。而且最近关于中微子性质的假说认为中微子的质量为0，或者非常小。因此，在计算中我们不需要考虑中微子。在放出正电子的衰变过程中，反冲原子的能量也可以忽略不计。 [英文](#)

我们得到钋放射的 α 射线的能量数值（单位是 10^6 eV ），如下表所示。由此，我们分别得到三个中子质量：1.0098、1.0092、1.0089。这些值基本一致。但是第一个值最精确，即从硼原子推导出的中子质量。镁和铝中的中子能量以及镁中正电子的能量都还不是十分确定。 [英文](#)

	W_H	W_R	W_n	W'_R	W_e	$Q \text{ (} 10^6 \text{ eV)}$	$Q \text{ 以质量为单位}$
B	8.05	0.23	3.3	0.59	1.5	+2.89	0.0031
Al	7.56	0.11	2	0.33	3.0	+2.34	0.0025
Mg	4.82*	0.21	1	0.48	1.5	+2.05	0.0022

* 这个正电子能量的最大可能值与实际观测并不相符，但是通过考虑与质子组的能量平衡，佩兰已经从博特和卡拉曼的实验中推导出了这个最大值。 [英文](#)

考虑到 ${}^9\text{Be}$ 原子核的稳定性，中子的质量本应该有一个最小值1.0107。但是在确定Be的质量时很可能存在0.001的误差。 [英文](#)

我们可以取中子质量为1.010，这个值的误差大概不会超过0.0005。 [英文](#)

取中子质量为1.010时，铍被钋放出的 α 粒子轰击所放出的中子的最大能量约为 $9 \times 10^6 \text{ eV}$ 。根据反应 ${}^7_3\text{Li} + {}^4_2\text{He} = {}^{10}_5\text{B} + {}^1_0n$ ，除非认为我们采用的 ${}^{10}_5\text{B}$ 的质量太大，超过真实值0.003，否则就无法解释当铍被钋放出的 α 粒子轰击时，会放射出慢中子的事实。 [英文](#)

如一些作者所设想的那样，如果原子核只包含质子和中子，那么当核内部一个中子转变成一个质子，并放射出负电子和中微子的反应可能就是 β 发射产生的原因。相反的过程也有可能发生：一个质子转变成一个中子，并放出一个正电子和一个中微子。 [英文](#)

取中子质量为1.010时，一个中子转变为一个质子和一个负电子的反应所释放的能量是 $2.1 \times 10^6 \text{ eV}$ ；一个质子转变成一个中子和一个正电子的反应所吸收的能量是 $3.1 \times 10^6 \text{ eV}$ 。 [英文](#)

(王静 翻译;王乃彦 审稿)

The Explanation of Supraconductivity

J. Frenkel

Superconductivity involves a transformation to a state of zero electrical resistance, apparently equivalent to an infinite conductivity. But here Russian physicist Yakov Frenkel suggests instead considering that the dielectric constant—a measure of a material's response to electric fields, due to polarisation—becomes infinite. While ordinary electrical current involves electrons moving freely through the material, a “polarisation current” might arise if the polarisation of atoms created by an applied electric field became infinite. Then, electrons could hop between atoms, creating coherent motion of one-dimensional chains of electrons sliding over the atomic lattice. Although Frenkel's contribution did not explain superconductivity, it did further an ultimately fruitful idea: that the phenomenon is somehow linked to coherent motion of charge carriers. 中文

IT is customary to describe the supraconductive state of a metal by setting its specific electric conductivity σ equal to infinity. I wish to direct attention to another possibility, namely, that the supraconductive state can be described much more adequately by setting equal to infinity the *dielectric constant* ϵ of the substance, its conductivity σ remaining finite or even becoming equal to zero. 中

文

The actual meaning of the new definition can be seen from a comparison of the mechanism of ordinary electric conduction (σ finite) and ordinary polarisation (ϵ finite). In the former case the electrons called “free” move *independently*, the conduction current being constituted by a drift motion due to the action of an external electric field and superposed on the unperturbed random motion of the individual electrons. In the second case the electrons called “bound” are displaced by the electric field simultaneously in the same direction, the polarisation current being due to an orderly collective motion of all the electrons. Under normal conditions the displacement of the electrons with regard to the respective atoms remains small compared with the interatomic distances; this corresponds to a finite value of the dielectric constant. The assumption that the latter becomes infinite means that under the action of an infinitesimal field the electrons are displaced simultaneously over finite distances, each of them passing successively from an atom to the next one, like a chain gliding over a toothed track. 中文

Such a collective motion of the “bound” electrons will constitute an electric current just as much as the individual motion of the free electrons, but a *polarisation* current rather than a *conduction* one. The electrostatic mutual action of the electrons moving collectively in a chain-like way will stabilise them against the perturbing action of the heat motion of the crystal lattice, which will result in the permanence of the polarisation current after the disappearance of the electric field by which it was started¹. This permanence, which has been erroneously interpreted as corresponding to an infinite value of the specific conductivity, must be interpreted in reality as corresponding to an *infinite value of the dielectric constant*. Now, how is it possible to explain the occurrence of such an infinite value? This turns out to be a very simple matter, the appropriate mechanism having been considered already by Hertzfeld, who, however, failed to give it the correct interpretation. Consider a chain of equally spaced atoms with

a polarisation coefficient α . This means that an isolated atom assumes under the action of an external field E an electric moment $p = \alpha E$. If the field E is acting in the direction of the chain, then in computing the polarisation of a certain atom we must add to it the field E' produced by all the other atoms in virtue of their induced electric moments. All these moments being the same, we get

$$E' = \frac{2p}{a^3} 2 \sum_{n=1}^{\infty} \frac{1}{n^3} = 4.52 \frac{p}{a^3};$$

and consequently

$$p = \alpha \left(E + 4.52 \frac{p}{a^3} \right),$$

whence

$$p = \frac{\alpha E}{1 - 4.52\alpha/a^3} = \alpha' E. \quad (1)$$

We thus see that with a finite value of α for an isolated atom, an infinite value of the effective polarisation coefficient α' for the atom-chain is obtained if

$$4.52\alpha \geq a^3. \quad (2)$$

[中文](#)

The sign $>$ corresponding to a negative value of α' need not be distinguished from the sign $=$; in both cases the atom chain is characterised by the instability of the electron chain connected with it. This instability, which has been noticed previously by Hertzfeld, was interpreted by him as an indication of the fact that the electrons no longer remain bound, but become free “conduction” electrons. Thus the inequality (2) was considered as characteristic of the metallic state in general. I believe that it is characteristic not of the metallic state but of the supraconductive state, a superconductor being rather a

dielectric with freely movable electron chains (that is, with $\epsilon = \infty$) than a metal. [中文](#)

According to a theory of the metallic state developed in a rather qualitative way by Slater² and recently greatly improved and generalised by Schubin³, the normal conductivity of a metal is due to a *partial ionisation* of the atoms, a certain fraction s of all the atoms becoming positive ions, and an equal portion (to which the corresponding electrons are attached) negative ions. If these electrons are bound very weakly, they may be considered as “free” in the usual sense of the word. The conductivity of a metal is equal to the sum of the conductivities due to these free electrons or negative ions on one hand and the positive ions or “holes” on the other. The mechanism of electrical conduction consists in the *individual* jumping of an electron from a negative ion to one of the neutral atoms surrounding it (which is thus converted into a negative ion), or from a neutral atom to a positive ion, which thus becomes a neutral atom, its rôle being switched over to the “donor”. We meet with the same type of electric conduction in electronic semi-conductors⁴. The chief distinction between a metal and a semi-conductor consists in the fact that in the former case $s > 0$ at the absolute zero of temperature (T) whereas in the latter case $s = 0$ at $T = 0$, increasing according to the Boltzmann equation ($s = ce^{-W/kT}$ where W is the ionisation energy) with the temperature. [中文](#)

The elements which are likely to become supraconductors form an intermediary group in the sense that at ordinary temperatures they are relatively poor conductors, like the ordinary semi-conductors; the dependence of their conductivity on the temperature is, however, of the same character as that of typical metals (negative temperature coefficient). This means that in the case of these intermediary elements or “half-metals”, we have to do with substances which are characterised by a practically constant value of the ionisation fraction

s. Their small conductivity can be explained either by a small value of s or by a small mobility of the individual electrons (which seems the more probable alternative in view of the correlation between supraconductivity and the Hall effect discovered by Kikoin and Lasareff). The fact that, in ordinary circumstances, that is, above the “transition temperature” T_c , these substances are not supraconductive, can be explained by the finite value of their dielectric constant as determined by the polarisability of ions stripped of the conduction electrons. The nature of the transition which takes place when the temperature T is decreased below T_c can thus be very simply interpreted by assuming that, at this temperature, s suddenly falls from a certain rather high value to *zero*, and that the polarisation coefficient α of the resulting *normal* atoms with their full complement of bound electrons satisfies the inequality (2)*. The very fact that the substance loses its conductivity (σ falling to zero along with s) thus transforms it from a metal into a dielectric with $\varepsilon = \infty$, that is, it becomes a supraconductor. 中文

Both the necessity and the sharpness of the transition $s \rightarrow 0$ (that is, $\sigma \rightarrow 0$ and $\varepsilon \rightarrow \infty$) can be easily understood if we assume that the state $s = 0$ has a smaller energy than the state $s > 0$. It results from Slater’s and especially from Schubin’s calculations that the *lowest* energy level for polar (ionic) states *may* correspond to a *finite* value of s , whether this lowest level lies below or above the energy level corresponding to $s = 0$. It can further easily be seen that the distance between the successive levels in a band of levels corresponding to a given value of s is very small compared with kT , even for extremely low temperatures (of the order of a few degrees K.). If, further, the *total* width of the band was also small compared with kT , the entropy of the state $s > 0$ could be calculated as $k \lg g$, where g is the statistical weight of the whole band, that is, the number of ways in which the state s is realised. Taking all possible distributions of the ns electrons (negative ions) and ns positive holes (positive ions) between the n

atoms, we get

$$g = \left[\frac{n!}{(ns)!(n - ns)!} \right]^2.$$

The transition $0 \rightarrow s$ is thus connected with an *increase* of entropy

$$\Delta\eta = 2k [n \lg n - ns \lg ns - (n - ns) \lg (n - ns)]. \quad (3)$$

In reality, the width of a band is of the order of 1 volt and therefore at least a thousand times larger than kT at the transition point. This will result in a much smaller entropy increase $\Delta\eta$. 中文

So long, however, as $\Delta\eta > 0$ it follows that the state $s=0$ must be stable at low temperatures and the state $s > 0$ at higher ones. 中文

The transition temperature T_c as determined by the equality of the free energies of the two states is given by

$$T_c = \frac{\Delta\varepsilon}{\Delta\eta} (\Delta\varepsilon = \varepsilon_s - \varepsilon_0). \quad (4)$$

Taking $s = \frac{1}{2}$ (which is probably an exaggeration) and calculating $\Delta\eta$ with the help of (3), we get $\Delta\eta = 1.7k_n$. If $T = 4^\circ$ (say) the transition energy $\Delta\varepsilon$ should be of the order of 14 small calories per gram atom. This value is greatly reduced if the width of the energy band under consideration is large compared with nT , its effective weight being accordingly small compared with g . 中文

We thus see that the second condition for supraconductivity is expressed by the inequality $\varepsilon_s > \varepsilon_0$ at $T = 0$. But this is not all. Equation (1) is a good approximation so long as the chain-like displacement of the electrons x is small compared with the interatomic distance a . When x approaches $\frac{1}{2}a$, the electrons are pushed back by a force which varies more rapidly than the first power of x and can be overcome through the quantum mechanism of the

tunnel effect. If a large number of electrons N are moving together in a chain-like way, they behave like a particle with an N -fold mass, the transition probability being correspondingly reduced. Now in his second theory of supraconductivity, Kronig⁵ has shown that a chain or, as he puts it, a “linear lattice”, of electrons, bound to each other in a quasi-elastic way, can be displaced through a periodic field of force (with a period a equal to the average spacing between the electrons) under the condition

$$h/b\sqrt{m} > a^2, \quad (5)$$

where h is Planck’s constant, m the mass of an electron and b is the rigidity coefficient of the “electron lattice”. Putting $b = \tau e/\alpha^{3/2}$ where τ is a numerical coefficient of the order 1, Kronig finds that the condition (5) is fulfilled if α is of the order of less than a few Ångström units. This seems to show that a “linear lattice”, that is, chain of electrons, is practically *always movable* with respect to the corresponding chain of atoms, provided the condition (2), which is much more restrictive, is fulfilled also. In fact, the latter condition seems to be the mathematical formulation of the possibility of treating the (bound) electrons as a kind of lattice. I do not believe in the reality of the three-dimensional lattices postulated by Kronig in his first paper. He has himself shown that such lattices, even if they exist, could not be moved through the ionic lattice. As a matter of fact, one-dimensional lattices or rather movable *chains* of bound electrons fully suffice for the explanation of supraconductivity. Such chains need not be movable in all directions. It is sufficient to assume that they should be movable in one particular crystallographic direction corresponding to the smallest spacing between the atoms, the dielectric constant being infinite for this direction and preserving a finite value for all the others. [中文](#)

In spite of its shortcomings, Kronig’s theory is certainly the nearest approach to the correct explanation of supraconductivity published

hitherto, the present theory differing from it more in form than in essence. The theory I advanced before, which was based on the supposed stabilisation of the free electrons (against heat motion) by their *electro-magnetic* action, was wholly erroneous in this particular respect. It was correct, however, in describing the motion of the electrons in the supraconductive state as an organised “collective” motion. This led to the result that a metal must possess when in this state an enormous diamagnetic susceptibility. This corollary subsists in the new theory and is corroborated by the fact recently discovered by Meissner that the magnetic permeability μ of a metal in the supraconducting state drops to zero. A superconductor can thus be described as a body with $\mu = 0$ and $\varepsilon = \infty$, its electrical conductivity σ in the exact sense of the word being either finite or even zero.

中文

A more complete account of the present theory will be published elsewhere. 中文

(133, 730-731; 1934)

References:

1. The effects of heat motion of the crystal lattice on the individual electrons are mutually cancelled. Cf. R. Kronig, *Z. Phys.*, **80**, 203; 1933.
2. *Phys. Rev.*, **35**, 509; 1930.
3. In the press.
4. Cf. J. Frenkel, *Nature*, **132**, 312, Aug. 26, 1933.
5. *Z. Phys.*, **80**, 203; 933.

* This inequality is probably satisfied for all metals, although not all of them are superconductors, because for true metal s remains finite (and practically constant) down to the absolute zero of temperature, while for superconductors it jumps to a finite value slightly above it .

超导电性的解释

弗伦克尔

超导电性涉及一个电阻突降为零的转变过程，而电阻为零似乎意味着一个无穷大的电导。但是在这篇文章中，俄国物理学家雅科夫·弗伦克尔则认为应该将介电常数视为无穷大，介电常数是表征材料由于极化引起的对电场响应程度的物理参数。虽然通常电流的形成就是电子自由通过材料的过程，但是如果由于电场导致的原子极化变为无穷大的话，也会产生“极化电流”。这样，电子可以在原子间跳跃，产生电子的一维链在原子晶格上滑移的相干运动。尽管弗伦克尔的这篇文章并没有解释清楚超导电性，但它确实促成了一个全新的想法：这一现象与载流子的相干运动存在某种联系。 [英文](#)

在描述金属的超导状态时，我们习惯于将金属的电导率 σ 定义为无穷大。我希望大家能够关注另外一种可能性，而这有可能是对超导状态更加合适的描述，即设物质的介电常数 ϵ 为无穷大，而电导率 σ 保持为有限值，甚至等于零。 [英文](#)

这个新定义的真正含义可以从普通电传导（ σ 为有限值）与普通电极化（ ϵ 为有限值）机制的比较中看出。就前者而言，电子可被看成是在独立地“自由”运动，传导电流是由外电场作用引起的漂移运动和单个电子无干扰的随机运动叠加而形成的。而对后者而言，受“束缚”的电子在电场的作用下沿同一方向同时产生位移，极化电流是由所有电子有序的集体运动产生的。一般情况下，电子相对于各自所属原子的位移比原子间的距离要小；这对应于介电常数是有限值的情形。如果我们假设介电常数的值为无穷大，那就代表，在无穷小电场的作用下，所有电子会同时移动一段有限的距离，每个电子连续地从从一个原子穿越至下一个原子，就像一根链子在锯齿形的轨道上滑动一般。 [英文](#)

“束缚”电子的这类集体运动所形成的电流与自由电子的单个运动形成的电流大小相等，但它是极化电流，而不是传导电流。以类链方式集体运动的电子之间的静电相互作用会克服由晶格热运动引起的扰动，从而使电子的这种运动稳定下来，这使得在引发了该运动的电场消失后，极化电流还将一直持续^[1]。这种电流的持续性曾经被错误地解释为是特定情况下电导率无穷大所致，而实际上应该用介电常数无穷大来进行解释。那么现在如何来解释介电常数无穷大的出现呢？事实上很简单，赫茨菲尔德已经想到了合适的机制，但是他并没有给出正确的解释。下面我们考虑由极化系数为 α 的等间距的原子组成的链。于是，在外场 E 的作用下，单个原子的电偶极矩就为 $p = \alpha E$ 。如果电场 E 沿链的方向，则在计算某一个原子的极化时，我们必须加上由于其他所有原子的感生电偶极矩所产生的电场 E' 。假设所有这些电偶极矩都相等，我们得到

$$E' = \frac{2p}{a^3} 2 \sum_{n=1}^{\infty} \frac{1}{n^3} = 4.52 \frac{p}{a^3}$$

因此

$$p = \alpha \left(E + 4.52 \frac{p}{a^3} \right)$$

所以

$$p = \frac{\alpha E}{1 - 4.52\alpha/a^3} = \alpha' E \quad (1)$$

由此可见，对于 α 是一个有限值的单个原子来说，如果

$$4.52\alpha \geq a^3 \quad (2)$$

我们得到原子链的有效极化系数 α' 的值为无穷大。 英文

(2) 式中符号“ $>$ ”相当于 α' 是负值，与符号“ $=$ ”没有区别；在这两种情况下，原子链可以用与其相连的电子链的不稳定性来表征。赫茨菲尔德以前就注意到了这种不稳定性，他还把这种现象解释为是电子不再受到束缚，而成为自由“传导”电子这一事实的一个标志。因此不等式(2)一般被认为是金属态的特征。我相信这并不是金属态的特征，而

是超导态的特征，超导体是一种具有可自由运动电子链（即 $\epsilon = \infty$ ）的电介质，而非金属本身。 [英文](#)

按照由斯莱特^[2]发展出的定性的金属态理论，以及最近由舒宾^[3]对该理论的改进和推广，金属的正常导电性是由于原子的部分电离引起的，某一部分原子 s 变成正离子，而相等的另一部分（携带相应电子的部分）变成负离子。如果这些电子受到的束缚很微弱，通常可以称其是“自由的”。金属的电导率等于由这些自由电子或负离子产生的电导率加上正离子或“空穴”产生的电导率之和。电传导的机制主要是一个电子从一个负离子单个地跳到附近的一个中性原子上（于是这个中性原子就转换成一个负离子），或从一个中性原子跳到一个正离子上，于是正离子就成为中性原子，充当“施主”的角色。半导体^[4]中具有相同类型的电传导机制。金属和半导体的主要区别在于：前者在温度（ T ）达绝对零度时， $s > 0$ ；而后者在 $T = 0$ 时， $s = 0$ ，且按照玻尔兹曼方程（ $s = ce^{-W/kT}$ ，其中 W 是电离能） s 随着温度的上升而增大。 [英文](#)

从某种意义上来说，能够成为超导体的元素形成了一个过渡状态的元素组，常温下，它们是传导性能相对比较差的导体，类似于普通的半导体；然而它们的电导率与温度的变化关系又和典型的金属（负温度系数）相同。当考虑这些过渡状态的元素或者“半金属”元素时，我们必然会遇到一些电离分数 s 实际为常数的物质。它们的弱导电性可以用很小的 s 值来解释，也可以用单个电子很小的迁移率来解释（考虑到基科因和拉萨雷夫共同发现的霍尔效应与超导电性之间的关系，这似乎是一个更合适的选择）。在通常情况下，也就是温度在“转变温度” T_c 以上时，这些物质不再是超导体，这一事实可以利用它们的介电常数为有限值来解释，这个有限值是由失去了传导电子的离子的极化率来决定的。对于当温度由 T 降至 T_c 之下时发生的相变的本质，我们可以简单地用以下两点假设进行解释：第一，在这个温度下， s 突然由某一相当高的值突变为零；第二，相应的带着所有束缚电子的普通原子的极化系数 α 满足不等式（2）*。物质失去导电性（ σ 与 s 变为零），于是由金属转变为 $\epsilon = \infty$ 的介质，也就是变成了超导体。 [英文](#)

如果我们假设 $s = 0$ 的态比 $s > 0$ 的态所具有的能量小，那么 $s \rightarrow 0$ 转变（即 $\sigma \rightarrow 0$ 和 $\epsilon \rightarrow \infty$ ）所具有的必然性和陡峭特点就很好解释了。这样的

结论可以从斯莱特尤其是从舒宾的计算中得到，这个计算显示：无论最低能级处于 $s=0$ 对应能级之上或之下，极化（离子）态的最低能级都可能对应于有限的 s 值。从而我们很容易看出，即使在极低的温度下（几K量级），给定 s 值对应能带中连续能级的间距远小于 kT 。如果能带的总带宽也小于 kT ，那么就可以按式子 $k \lg g$ 来计算 $s>0$ 的态的熵，其中 g 是整个能带的统计权重，即得到态 s 所有方式的数目。考虑 n 个原子间 ns 个电子（负离子）和 ns 个正空穴（正离子）所有可能的分布，我们得到：

$$g = \left[\frac{n!}{(ns)!(n - ns)!} \right]^2$$

因此，与 $0 \rightarrow s$ 转变相应的熵增加是

$$\Delta\eta = 2k [n \lg n - ns \lg ns - (n - ns) \lg (n - ns)] \quad (3)$$

实际上，带宽的数量级是1电子伏，因此在温度处于转变点时，带宽至少是 kT 的一千倍。这将得到一个非常小的熵的增加量 $\Delta\eta$ 。 [英文](#)

然而，只要 $\Delta\eta > 0$ ， $s = 0$ 的态在低温下一定是稳定的， $s > 0$ 的态在更高的温度下也一定是稳定的。 [英文](#)

转变温度 T_c 由两个态的自由能相等决定，由下式给出：

$$T_c = \frac{\Delta\varepsilon}{\Delta\eta} (\Delta\varepsilon = \varepsilon_s - \varepsilon_0) \quad (4)$$

取 $s = \frac{1}{2}$ （它可能是一个夸大值），根据（3）式计算 $\Delta\eta$ ，我们得到 $\Delta\eta = 1.7k_n$ 。假设 $T = 4 \text{ K}$ ，则转变能 $\Delta\varepsilon$ 应是每克原子14卡的量级。如果在考虑的范围内存带的带宽比 nT 大，那么这个值会大幅度降低，其有效权重会相应地比 g 小。 [英文](#)

于是，我们发现，超导电性的第二个条件应该表示为在 $T=0$ 时满足不等式 $\varepsilon_s > \varepsilon_0$ 。但这还不是全部。只要电子的类链位移 x 小于原子间距 α ，（1）式就是一个很好的近似。当 x 约等于 $\frac{1}{2}\alpha$ 时，电子则被一个力推回去，这个力比 x 的一次幂变化更快，并能被量子机制的隧道效应所克服。如果大量电子 N 以类链方式整体运动，它们就犹如具有 N 倍质量的一个粒子一样，转变概率将显著下降。克罗尼格^[5]在他的第二个超导理论

中已指出，电子链（他所说的“线形晶格”）以准弹性方式彼此束缚，在满足条件（5）式的情况下可以通过力的周期场（周期 α 等于电子之间的平均距离）。

$$h/b\sqrt{m} > \alpha^2 \quad (5)$$

式中， h 是普朗克常数， m 是电子质量， b 是“电子晶格”的刚性系数。令 $b = \tau e/\alpha^{3/2}$ ，其中 τ 是一个量级为1的系数，克罗尼格发现，如果 α 的量级小于几埃，则条件（5）式是满足的。这似乎表明，当限制性更强的条件（2）式也满足时，“线性晶格”即电子链相对于相应的原子链实际上总是可运动的。实际上，后一条件似乎是能否将（束缚）电子当作一种晶格来处理的可能性的数学描述。我并不认为，克罗尼格在他的第一篇文章中假设的三维晶格是真实存在的。他自己也表明，这类晶格即使存在也不能穿过离子晶格。事实上，一维晶格或可运动的束缚电子链完全可以解释超导电性。这类链并不需要在所有方向上都能运动。它们只要做如下的假设就足够了，即它们在一个特殊的晶体学方向上应该是可运动的，这个特殊方向对应于原子间的距离最小，而且介电常数在这个方向上为无穷大，而在其他方向上总保持一个有限值。 [英文](#)

克罗尼格的理论虽然存在不足，但它确实是迄今发表的对超导电性最接近正确的解释，我的理论与其的差别更多是在形式上，而非本质上的。我以前提出的基于假设在电磁作用下自由电子（相对于热运动）的稳定性的理论在这个特定方面是完全错误的。但是，在将超导态中电子的运动描述为有组织的“集体”运动这点是正确的。这就要求金属在这种态下必须具有巨大的抗磁性的磁化率。这个推论在新理论中成立，而且被迈斯纳最近发现的事实所证实，迈斯纳的实验显示金属的磁导率 μ 在超导态中会下降到零。因此超导体可以被表述为 $\mu = 0$ 和 $\epsilon = \infty$ 的物体，更确切地说，其电导率 σ 或者是一个有限值，或者就是零。 [英文](#)

这一理论更完整的叙述将在其他地方发表。 [英文](#)

（沈乃澍 翻译；郑东宁 审稿）

* 这个不等式几乎对所有金属来说都是成立的，尽管并不是所有的金属都是超导体，因为对于真正的金属而言，在温度下降到绝对零度的过程中， s 将保持一个有限值（实际上是常数），然而对超导体而言，它会跳跃成为比先前略大的一个有限值。

Modern Ideas on Nuclear Constitution

G. Gamow

George Gamow here reviews advances in the theory of nuclear structure. With the discovery of the neutron, physicists now considered stable nuclei to be composed of neutrons and protons. As Gamow points out, Heisenberg's theory of nuclear structure suggested that small nuclei should have roughly equal numbers of the two particles, and that an imbalance toward more neutrons should grow with increasing atomic mass, thereby counteracting the electrical repulsion between protons. Gamow considers the stability of nuclei to both beta and alpha decay, which could be understood only partially in current theory. The approximate proportionality of nuclear radius to the cube root of the atomic mass suggested that the density of the nucleus remains roughly constant. [中文](#)

WHEN the complexity of atomic nuclei was proved by the existence of spontaneous and artificial nuclear transformations, a very important question arose: From which of the elementary particles are the different nuclei built up? It seemed that this question could be simply answered as there were only two particles with pretensions to be elementary: the proton and the electron. The protons had to account for the main part of the nuclear mass and the electrons had to be introduced to reduce the positive charge to the observed value. For

example, the nucleus of bismuth, with atomic weight 209 and atomic number 83, was considered to be constructed from 209 protons and $209 - 83 = 126$ electrons. It was also accepted as very probable that these elementary particles build up inside the nucleus certain complex units constructed from four protons and two electrons each (α -particles). All this construction was in good agreement with the experimental evidence, as electrons, protons and α -particles were really observed being emitted in nuclear transformations. 中文

The theory treating the nuclei as constructed of α -particles, some protons and a certain number of electrons, was worked out by Gamow. Although this theory gave some interesting results as to the general shape of the mass-defect curve and the conditions of emission of α -particles, it met with serious difficulties. It was very difficult to understand, on the basis of the quantum theory of the electron, how the electron can exist in a space so small as that limited by the nuclear radius. It was also not clear why the nuclear electrons, behaving in quite a strange and obscure way, do not affect the processes of emission of the heavy nuclear particles, protons and α -particles.

中文

About two years ago, it was shown by Chadwick that the experimental evidence forces us to recognise the existence of a new kind of particle, the so-called neutron, also with claims to be held to play an important rôle in nuclear structure. The discovery of neutrons considerably simplified the difficulties about electrons in nuclei. One could now suppose that the nuclei were completely constructed of neutrons and protons (for example, the nucleus of bismuth from 83 protons and $209 - 83 = 126$ neutrons) which probably sometimes unite to form an α -particle (two neutrons and two protons). Thus the first of the above-mentioned difficulties was, so to say, hidden inside the neutron, while the second one was actually removed. 中文

On the basis of these new ideas, Heisenberg succeeded in building up

a general theory of nuclear structure, accounting for the main features of nuclear stability. The basis of his theory is certain assumptions about the forces acting between neutrons and protons. It seems most rational to accept the view that the interaction between particles of the same kind is only due to electric charges (that is, no forces between two neutrons and the usual Coulomb repulsion between two protons), while between two different particles (neutron and proton) strong exchange forces come into play. These last forces are probably of the same kind as the forces between atoms playing the main rôle in quantum chemistry, and may be considered as due to the exchange of charge between the two particles in question. 中文

This hypothesis explains at once why the number of nuclear neutrons for heavy elements is considerably greater than the number of protons (that is, why the ratio of atomic weight to atomic number increases for heavier elements). In fact, if we neglect the coulomb forces, the most stable state of the nucleus will correspond to equal numbers of neutrons and protons, as in this case all the possibilities of binding (by attracting exchange forces), between protons and neutrons are saturated. The presence of the Coulomb repulsion between protons will, however, shift the optimum in the direction of a smaller number of protons and the position of lowest potential energy of our system will correspond to the larger proportion of neutrons. As the importance of the Coulomb forces increases with the nuclear charge, one can understand that an equal number of neutrons and protons is possible only for the lightest elements (first ten elements of the periodic system), while for heavier ones the number of neutrons predominates (126 neutrons and only 83 protons in bismuth). 中文

Accepting the simplest form for the law of variation of the exchange forces with distance:—

$$I = a \cdot e^{-br} \quad (1)$$

and applying the quantum statistical method, Heisenberg calculated the behaviour of the nuclear model constructed from n_1 neutrons and n_2 protons. The result is that the particles are rather uniformly distributed inside a certain volume proportional to the total number of particles. This result fits very well with evidence otherwise obtained, that the density inside the nucleus is rather uniform and does not depend greatly on the atomic weight. The formula obtained for the total binding energy E of the nucleus as a function of n_1 and n_2 looks rather complicated and depends, of course, on the numerical values of the coefficients a and b in the expression (1) for the exchange force. Comparing this formula with experimental values of the mass defects of different nuclei, one can estimate the values of a and b . One finds thus: $a = 4.05 \times 10^{-5}$ erg; $b = 1.25 \times 10^{12}$ cm.⁻¹. 中文

Very interesting consequences can also be obtained from Heisenberg's theory concerning the question of nuclear stability. It is easily understood that nuclei with a high positive electric charge must tend to emit positive particles. From the point of view of the energy balance, the most favourable case for such emission is the emission of an α -particle, as this removes from the nucleus a large amount of negative energy (the binding-energy of the α -particle itself), which is equivalent to the supply of an equal quantity of positive energy. The condition for the possibility of α -emission can be simply formulated if we consider it as a simultaneous subtraction of two neutrons and two protons from the nucleus in question. The work necessary for such subtraction is evidently

$$\frac{\partial E}{\partial n_1} \Delta n_1 + \frac{\partial E}{\partial n_2} \Delta n_2$$

or, as $\Delta n_1 = \Delta n_2 = -2$,

$$-2 \left(\frac{\partial E}{\partial n_1} + \frac{\partial E}{\partial n_2} \right).$$

To make a spontaneous α -disintegration possible, this quantity must be smaller than the above mentioned energy-supply due to the binding energy $\Delta M_\alpha c^2$ of the α -particle from neutrons and protons. (The difference appears as the kinetic energy of the emitted particle.) Thus the condition for α -decay will be:

$$-2\left(\frac{\partial E}{\partial n_1} + \frac{\partial E}{\partial n_2}\right) < \Delta M_\alpha c^2 \quad (2)$$

In Fig. 1, the ratio of the number of neutrons to the number of protons is plotted against the number of protons for all known isotopes. The α -stability curve as calculated from formula (2) is represented by a broken line (curve I) and one can see that it is situated too low. One notices, however, that the theoretical curve, apart from absolute values, gives a good idea of the general form of this stability limit. We may notice that the condition for the spontaneous emission of a proton:

$$-\frac{\partial E}{\partial n_2} < 0 \quad (2')$$

will give us a stability limit located very far to the right of the α -stability curve, which means that spontaneous proton decay could only take place for very heavily charged nuclei (atomic number > 200). On the other hand, the condition for the emission of a neutron:

$$-\frac{\partial E}{\partial n_1} < 0 \quad (2'')$$

is never fulfilled, which can easily be understood if we remember that neutrons, having no charge, are not at all repelled by nuclei. 中文

We must now turn our attention to the question of the emission of light particles. From the point of view of the neutron-proton model of

the nucleus, we must accept the view that the process of ordinary β -emission is due to the transformation of a nuclear neutron into a proton with the liberation of negative charge in the form of an electron:

$$n \rightarrow p + \bar{e}.$$

中文

On the other hand, the recent discovery of the Joliot's of elements emitting positive electrons suggests the possibility of the reverse process:

$$p \rightarrow n + e^+.$$

中文

We can easily estimate the stability limits for such processes if we consider the emission of a nuclear electron as the subtraction from the nucleus of a neutron and simultaneous addition of a proton. The condition for the positive energy balance of such a transformation will evidently be:

$$-\frac{\delta E}{\delta n_1} + \frac{\delta E}{\delta n_2} < \Delta M_n \cdot c^2, \quad (3)$$

where ΔM_n is the mass defect of a neutron as constructed from a proton and an electron. In an exactly analogous way we obtain for the possibility of emission of a positive electron the condition:

$$-\frac{\delta E}{\delta n_2} + \frac{\delta E}{\delta n_1} < \Delta M_p \cdot c^2, \quad (4)$$

where ΔM_p is the mass defect of a proton as constructed from a neutron and a positive electron. From (3) and (4) we can conclude that the nucleus can be stable relative to electron emission only if

$$-\Delta M_p c^2 < -\frac{\partial E}{\partial n_1} + \frac{\partial E}{\partial n_2} < \Delta M_n c^2,$$

conditions which correspond in the stability diagram (Fig. 1) to a very narrow band (curves II and III)*, in contradiction with the experimental evidence. 中文

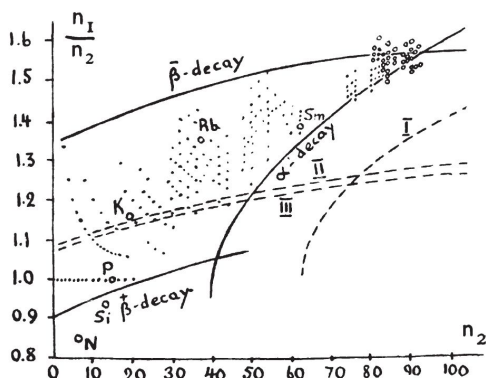


Fig. 1. A map of all known nuclei. Stable nuclei are indicated by full points, unstable nuclei by small circles. 中文

The stability region can, however, be made much broader if we consider more closely the energy conditions connected with electronic emission from nuclei. The point is that for a given total number of neutrons plus protons (that is, for given atomic weight) the nuclei are considerably more stable if the number of protons is even (even atomic number). The reason for this is that, with the increasing number of protons, each second one will lead to the formation of a new α -particle, and consequently correspond to larger liberation of energy. Thus if we plot the binding energy of isobaric nuclei against the atomic number (Fig. 2), the points corresponding to even-numbered elements will lie on a lower curve than those corresponding to the odd numbers. As can be seen from the diagram, this will have the result that for a series of elements extending some way both to the left and to the right side of the minimum, the emission of one electron (either negative or positive) will be energetically impossible. In such cases only the simultaneous emission of two electrons can be considered, but, as can be estimated from general theoretical

considerations, such a double emission has extremely small probability. The possibility is not excluded that the natural β -activity of potassium and rubidium has its origin in such a double process, which would easily explain their extremely long period of life. 中

文

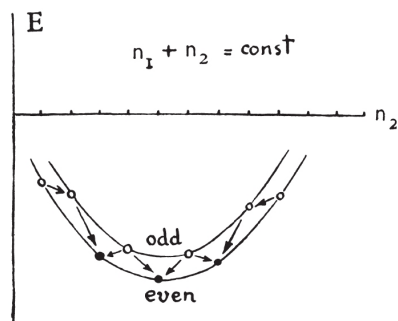


Fig. 2. Mass defect curves for typical isobaric nuclei. ●, stable nuclei; ○, unstable nuclei.

中文

According to these considerations we must push the limit of $\bar{\beta}$ -stability upwards and the limit of β^+ -stability downwards, and thus get a considerably broader stability region. It can be seen from Fig. 1 that theoretical limiting curves give a good idea of the form of the actual stability limits, although, just as in the case of α -decay, the curves go again too low. It seems that both discrepancies have a common origin. 中文

In Fig. 1, the points corresponding to unstable nuclei are shown by small circles. One notices that in the region of the heavy elements, where α - and β -stability curves run rather close to one another (and possibly cross), the sequences of α -disintegrations followed by two β -disintegrations are possible. For the lighter elements only a few cases of spontaneous disintegration are at present known. Samarium (most probably its lightest isotope) emits α -particles of about 1.5 cm. range and has an average life of about 10^{12} years. The lightest isotopes of nitrogen, silicon and phosphorus (N^{13} , Si^{27}_{14} , P^{30}_{15}), unknown in Nature and produced artificially by the Joliot's by α -bombardment of boron,

magnesium and aluminium, give β^+ -particles with an energy of 1–2 million volts and possess life-periods of several minutes. 中文

The $\bar{\beta}$ -emission from potassium and rubidium must be explained either as a double electron emission from their heavier isotopes (K_{19}^{41} and Rb_{37}^{87}) or as due to some unknown isotopes of chlorine and bromine resulting from a very short range α -emission of the above mentioned elements (probably from K_{19}^{40} and Rb_{37}^{86}). As these ranges in air, as calculated theoretically from the value of the corresponding decay constants, are 0.24 cm. and 0.63 cm. respectively, one can understand why the α -particles have not yet been detected. Thus we see that our general theoretical considerations fit rather nicely with the experimental evidence. 中文

We now turn our attention to the details of the processes of emission of α -particles and electrons, and the connexion of the disintegration energy with the average period of life. The process of α -emission can be explained on the basis of the ordinary wave equation of Schrödinger as the velocities of the emitted α -particles are small compared with the velocity of the light. It was shown by Gamow, and independently by Gurney and Condon, that the long life of α -decaying bodies is due to the fact that the α -particle leaving a nucleus must cross a very high potential barrier, the transparency of which is extremely small and decreases very rapidly with the decrease of the energy liberated in the disintegration. Theory leads us to the following formula for the decay-constant λ as a function of the α -particle velocity v :

$$\lambda = \frac{4h}{mr_0^2} e^{-\frac{8\pi^2 e^2}{h} \frac{(Z-2)}{v} + \frac{16\pi e \sqrt{m}}{h} \sqrt{Z-2} \sqrt{r_0}} \quad (5)$$

where Z is the atomic number of the disintegrating element and r_0 the nuclear radius. Accepting r_0 for radioactive elements to be of the order of magnitude 10^{-12} cm., one obtains very good agreement between the calculated and measured values of λ and can explain theoretically the

empirical relation between $\lg \lambda$ and ν found by Geiger and Nuttall.

中文

For complete agreement one must, however, accept the view that the nuclear radius r_0 changes from one element to another in such way that the density of the nucleus remains constant ($r_0 \sim \sqrt[3]{A}$). Formula (5) permits us also to estimate one of the values λ or ν if the other is measured. Thus, for example, the range of the α -particles of radium C, estimated from this formula to be equal to 4 cm., is in good agreement with the value found later by Rutherford, and the period of life of the very short lived product radium C' given by this formula (10^{-3} sec.) fits well with the recent measurements of Jacobsen. 中文

It is also interesting to notice that formula (5) may be successfully applied in the region of the lighter elements. According to (5) the period of life of samarium as estimated from the velocity of its α -particles must be about 10^{12} years, in good agreement with the observed value. 中文

In the process of α -decay, it may often happen that the nucleus of the product of disintegration is constructed in an excited state, which corresponds to the emission of α -groups with slightly smaller energy (fine-structure of α -rays). The formula helps us to understand the relative intensities of such α -groups and also permits us to draw certain important conclusions about the quantum numbers of the different excited nuclear levels. On the other hand, it also explains the small number of so-called long-range α -groups corresponding to the disintegration of excited nuclei. 中文

In contrast with the theory of α -decay, the understanding of the process of β -disintegration presents serious difficulties. First of all, the electrons emitted in β -decay possess a continuous distribution of energy, which seems to be in contradiction with the law of conservation of energy. It was pointed out by Bohr that the law of

conservation of energy need not necessarily hold for processes involving nuclear electrons for which the modern quantum theory is not applicable. But, as was shown by Landau, the rejection of the conservation law for energy will be connected with very serious difficulties in the general gravitational theory, according to which the mass present inside a certain closed surface is entirely defined by the gravitational field on this surface. It was proposed by Pauli that one might retain the energy conservation law by the introduction of a new kind of particle called a “neutrino”. These neutrinos, having no electric charge and possessing very small (or even vanishing) mass, would be practically unobservable in all experiments and could easily take away the surplus energy of β -decay. The existence of such particles is, however, at present rather doubtful. 中文

An attempt to construct a theory of β -disintegration on the basis of Dirac's relativistic wave equation, treating the emission of a nuclear electron in a similar way to the emission of light quanta by an atom, has recently been made by Fermi. In this theory, one accepts the view that the transformation of a nuclear neutron into a proton is connected with the creation of an electron and a neutrino, which, being born, leave the nucleus, dividing between them the energy liberated in this transformation. Accepting a definite value for the interaction energy giving rise to such transformations (of the order of magnitude of about 10^{-14} erg), Fermi obtains reasonable values for the decay constants of β -disintegrating elements and a good fit with the correlation curve between the decay constant and the maximum energy of the β -particles as found by Sargent. 中文

An interesting consequence of this theory, which, however, is much more general and will hold for every theory treating electron emission as the result of the transformation of a neutron into a proton, is a definite exclusion rule for β -decay. According to this rule, β -transformations in which the original nuclei and those produced

possess different spins are not all permitted, and can only happen with a rather reduced probability (about a hundred times less often than transformations in which the spin does not change). This explains at once the two different curves obtained by Sargent as due to permitted and not permitted transformations. It has been shown by Gamow that the application of the above mentioned exclusion rule for β -decay to the analysis of radioactive families gives very good results and permits us to give definite spin values to normal and excited states of radioactive nuclei. [中文](#)

(133, 744-747; 1934)

* From the equations $n = p + \bar{e} + \Delta M_n c^2$ and $p = n + \bar{e} + \Delta M_p c^2$, we obtain $\Delta M_n c^2 - (-\Delta M_p c^2) = \Delta M_n c^2 + \Delta M_p c^2 = \bar{e} + \bar{e} = 2mc^2 = 1.6 \times 10^{-6}$ erg. This corresponds in Fig. 1 to a breadth of the stable region of about 0.016 units along the ordinate.

核组成的现代思想

伽莫夫

在这篇文章中，乔治·伽莫夫回顾了核结构理论的发展状况。随着中子的发现，现在物理学家认为稳定的原子核由质子和中子构成。正如伽莫夫指出的那样，海森堡的核结构理论认为小的原子核应该含有大体相等数量的两种粒子，但随着原子质量的增加平衡会被打破，中子的数目会变得更多，这会抵消质子间的静电斥力。伽莫夫认为当前的理论只能部分解释原子核相对 α 衰变和 β 衰变的稳定性。原子核半径与原子质量的立方根粗略成正比表明原子核的密度大致保持不变。 [英文](#)

当自发和人工的核转变的存在证明了原子核的复杂性时，一个很重要的问题出现了：不同的原子核是由哪些基本粒子组成的？这个问题似乎可以简单地回答，因为自命是基本粒子的只有两类：质子和电子。原子核的质量主要是由质子贡献的，而电子的引入是为了减少正电荷以便符合实验的观测值。例如，原子量209、原子序数83的铋原子核被认为是由209个质子和 $209 - 83 = 126$ 个电子组成的。大家还认为这些基本粒子在原子核内构建某种由四个质子和两个电子组成的复合单元（ α 粒子）也是很有可能的。所有这些结构都与实验结果吻合得很好，因为我们确实在核转变的实验中观测到了所放出的电子、质子和 α 粒子。

[英文](#)

伽莫夫发展了一种理论，即原子核由 α 粒子、一些质子和一定数目的电子组成。虽然这个理论给出了一些有趣的结果，如原子核质量亏损曲线的一般形状和原子核发射 α 粒子的条件，但同时也遇到了严重的困难。根据电子的量子理论，我们难以理解电子如何能存在于原子核半径所限制的微小空间内。我们也不清楚原子核中电子的行为为何如此奇

怪，且难以理解原子核的电子为何不会影响重核的粒子（质子和 α 粒子）的发射过程。 [英文](#)

约两年前，查德威克指出，实验证据使我们不得不承认存在一类新的粒子，即所谓的中子，它们在原子核结构中扮演了重要角色。中子的发现大大简化了原子核内有关电子的困难。现在我们可以假设原子核完全是由质子和中子组成的（例如，铋元素的原子核是由83个质子和 $209 - 83 = 126$ 个中子组成），而质子和中子有时也可能结合成一个 α 粒子（两个质子和两个中子）。因此，可以这么说，上面提到的第一个困难被隐藏在中子内部，而实际上第二个困难这时已经被排除。 [英文](#)

根据这些新的思想，海森堡成功地建立了一个原子核结构的普遍理论，用来解释原子核稳定性的主要特征。他的理论基础是建立在某些关于质子和中子之间存在相互作用力的假设上的。看起来最合理且可接受的观点是，认为同类粒子之间的相互作用仅由电荷产生（即在两个中子之间不存在力的作用，而在两个质子之间通常有库仑排斥力），而在两类不同的粒子（中子和质子）之间有强的交换力起作用。这后一种力很可能与量子化学中起主要作用的原子间的作用力类同，可以认为是由相关的两个粒子之间电荷交换产生的。 [英文](#)

以上的假设立即解释了为何重元素原子核中的中子数远大于其质子数（即为何原子量与原子序数之比对较重元素而言是逐渐增大的）。实际上，如果我们忽略库仑力，原子核最稳定的状态将相应于质子数与中子数相等的情况，在这种情况下，质子与中子之间所有可能的结合方式（通过吸引的交换力）趋于饱和。但是，由于质子之间存在库仑排斥现象使得原子核偏离最佳状态朝向较小的质子数，这时，系统的最低势能状态将对应于较大比例的中子数。由于库仑力的重要性随着核电荷的增大而增加，这时人们可以理解只有对那些最轻的元素（元素周期表中的前10个元素），同等数目的中子和质子才是可能的；而对于较重的元素，其中子数在数量上就会占优势（如铋元素由126个中子和83个质子组成）。 [英文](#)

对交换力随距离变化的规律采用最简单的形式：

$$I = a \cdot e^{-br} \quad (1)$$

并应用量子统计方法，海森堡计算出了由 n_1 个中子和 n_2 个质子所构建的核模型的行为。结果是，在与粒子总数成正比的一定体积内，粒子的分布相当均匀。这项结果与从其他途径得到的结果是非常吻合的，即核内的密度分布相当均匀，且与原子量无太大关系。而以原子核总的结合能 E 作为 n_1 和 n_2 的函数得到的关系式似乎非常复杂，当然， E 与交换力表达式（1）中的系数 a 和 b 的数值也是有关的。将这个公式与不同原子核的质量亏损的实验值进行对照，我们可以估算出 a 和 b 的值，得到的结果是： $a = 4.05 \times 10^{-5} \text{ erg}$ ， $b = 1.25 \times 10^{12} \text{ cm}^{-1}$ 。 [英文](#)

从海森堡有关核稳定性问题的理论中，我们也能获得很有趣的结果。我们很容易理解具有高正电荷的原子核必然趋于发射出带正电的粒子。根据能量守恒的观点，对这类发射最有利的情况是发射一个 α 粒子，即从核中带走了大量的负能量（ α 粒子自身的结合能），这相当于给原子核提供了同样多的正能量。如果把 α 粒子的发射认为是从相关的核内同时减去两个中子和两个质子，则 α 粒子发射的可能性条件可以被简单地表述出来。显然，这类过程扣除所需的能量为

$$\frac{\delta E}{\delta n_1} \Delta n_1 + \frac{\delta E}{\delta n_2} \Delta n_2$$

或，当 $\Delta n_1 = \Delta n_2 = -2$ 时，

$$-2 \left(\frac{\delta E}{\delta n_1} + \frac{\delta E}{\delta n_2} \right)$$

[英文](#)

要使一个自发的 α 衰变成为可能，这个量必须小于上述由中子和质子形成 α 粒子时放出的结合能 $\Delta M_\alpha c^2$ 。（两者的能量差将作为放出的粒子的动能。）因此， α 衰变的条件是：

$$-2 \left(\frac{\delta E}{\delta n_1} + \frac{\delta E}{\delta n_2} \right) < \Delta M_\alpha c^2 \quad (2)$$

[英文](#)

图1中画出了所有已知同位素的中子数和质子数的比值与其质子数的关系。根据公式(2)计算得到的 α 稳定性曲线用虚线(曲线I)表示,从中可以看到,它所处的位置非常低。然而我们注意到,不考虑绝对值的大小,理论曲线还是让我们对 α 稳定性的界限有了很好的了解。我们可能会注意到,质子的自发发射条件为:

$$-\frac{\delta E}{\delta n_2} < 0 \quad (2')$$

这里给出的发射质子的稳定性界限远离 α 稳定性曲线的右边,这意味着只有很重的带电核(原子序数大于200)才能发生自发的质子衰变。另一方面,对 neutron 发射的条件:

$$-\frac{\delta E}{\delta n_1} < 0 \quad (2'')$$

是永远不可能满足的,如果想到不带电荷的中子绝不被原子核排斥,我们将很容易理解这一点。 [英文](#)

现在我们必须将注意力转回到轻粒子发射的问题上来。根据核的中子-质子模型,我们必须采纳以下观点,即通常的 β 发射过程是由于核的中子以电子的形式释放出负电荷而转变为质子所引起的:

$$n \rightarrow p + e^-$$

[英文](#)

另一方面,约里奥夫妇最近发现了发射正电子的元素从而揭示了以上逆过程出现的可能性:

$$p \rightarrow n + e^+$$

[英文](#)

只要我们认为核电子的发射相当于从原子核内拿走一个中子同时加入一个质子,则我们很容易估计出这个过程的稳定性极限。这种转变的正能量守恒条件显然将是:

$$-\frac{\delta E}{\delta n_1} + \frac{\delta E}{\delta n_2} < \Delta M_n \cdot c^2 \quad (3)$$

式中， ΔM_n 是一个质子和一个电子构成一个中子的质量亏损。通过严格类比，我们得到可能发射正电子的条件为：

$$-\frac{\delta E}{\delta n_2} + \frac{\delta E}{\delta n_1} < \Delta M_p \cdot c^2 \quad (4)$$

式中， ΔM_p 是一个中子和一个正电子构成一个质子的质量亏损。根据（3）式和（4）式，我们可以断定，仅在以下条件下，即

$$-\Delta M_p c^2 < -\frac{\delta E}{\delta n_1} + \frac{\delta E}{\delta n_2} < \Delta M_n c^2$$

核相对电子发射可能是稳定的，这个条件对应于稳定性图（图1）中一条很窄的带（曲线II和曲线III）*，这与实验结果相矛盾。 [英文](#)

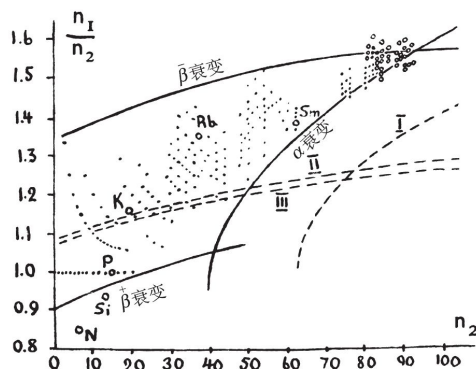


图1．所有已知原子核的图。稳定核用黑点表示，不稳定核用小圆圈表示。

[英文](#)

然而，如果我们进一步考虑与原子核的电子发射有关的能量条件，以上讨论的稳定区域可以变得更宽。问题在于对于一个给定的中子和质子的总数（即对于给定的原子量），如果质子数是偶数（偶原子序数），那么原子核是相当稳定的。理由是，随着质子数的增加，每两个质子将导致一个新的 α 粒子的形成，从而释放更多的能量。因此如果我们画出同量异位核的结合能相对其原子序数的关系图（图2），则对应于偶数元素的点位于比奇数元素相应点更低的曲线上。如图所示，结果将是，对延伸到位于最小值两侧的一系列元素从能量角度上来看是不可能发射电子（不管是负电子或正电子）的。在这种情况下，只能认为两个电子

同时发射。正如根据一般的理论估计的那样，这类成对电子发射的概率是很小的。但并不排除元素钾和铷的天然 β 放射性源于这类成对电子的发射过程，这也容易解释它们为何具有极长的寿命。 [英文](#)

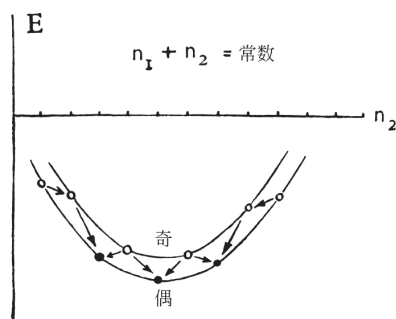


图2．典型的同量异位素核的质量亏损曲线。●稳定核；○不稳定核。

[英文](#)

根据以上的考虑，我们必须将 $\bar{\beta}$ 稳定性的极限向上推，而将 β^+ 稳定性的极限向下推，从而得到相当宽的稳定性区域。由图1可见，尽管与 α 衰变的情况一样，曲线的位置仍然很低，但是理论的极限曲线对实际的稳定性极限形状有一个很好的认识作用。似乎以上两类差异都出于相同的原因。 [英文](#)

在图1中，对应的不稳定核用小圆圈表示。我们注意到，在重元素区域内 α 和 β 的稳定性曲线彼此很接近（可能有交叉），发生 α 衰变后紧接着两次 β 衰变的顺序是可能的。对于较轻的元素，目前我们只知道存在少数的自发衰变情况。如钐（极有可能是最轻的同位素）放出射程约为1.5cm的 α 粒子，且平均寿命约为 10^{12} 年。而氮、硅和磷各自最轻的同位素（ ^{13}N , ^{27}Si , ^{30}P ）在自然界中不存在，而是由约里奥夫妇利用 α 粒子分别轰击硼、镁和铝人工产生的，这些人工同位素放出能量为1~2兆电子伏，寿命约为几分钟的 β^+ 粒子。 [英文](#)

钾和铷的 $\bar{\beta}$ 发射一定也可以解释成要么是它们较重的同位素（ ^{41}K 和 ^{87}Rb ）发生了双电子发射，要么是源于上述元素（可能来自 ^{40}K 和 ^{86}Rb ）非常短射程的 α 粒子发射的一些氯和溴的未知同位素。根据相应的衰变常数进行理论计算，可以得到它们在空气中的射程分别为0.24 cm和0.63 cm，这样我们就可以理解为何 α 粒子尚未被探测到。这里我们看到，通常的理论推算与实验结果较好地符合了。 [英文](#)

我们现在将注意力转到 α 粒子和电子发射的详细过程以及衰变能量与平均寿命的关系上来。 α 粒子发射过程基于普通的薛定谔波动方程可以解释为，发射的 α 粒子的速度是小于光速的。格尼、康登他们与伽莫夫都曾独立地指出， α 粒子衰变体的长寿命是由于从核中逃逸的 α 粒子必须穿过很高的势垒，而势垒的透射率极小，且随着衰变过程释放出能量的减小而迅速减小。理论导出以衰变常数 λ 作为 α 粒子速度 v 函数的公式：

$$\lambda = \frac{4h}{mr_0^2} e^{-\frac{8\pi^2 e^2}{h} \frac{(Z-2)}{v} + \frac{16\pi e \sqrt{m}}{h} \sqrt{Z-2} \sqrt{r_0}} \quad (5)$$

式中， Z 是衰变元素的原子序数， r_0 是核半径。采用放射性元素的 r_0 是在 10^{-12} cm的量级，这使得 λ 的计算值与测量值得到很好的符合，而且可以在理论上解释由盖革和努塔耳得到的 $\lg \lambda$ 和 v 之间的经验关系式。

英文

然而，为了使理论和实验可以完全符合，我们必须采用以下观点，在核的密度保持恒定（ $r_0 \sim \sqrt[3]{A}$ ）的条件下，不同元素之间的核半径 r_0 是变化的。如果 λ 和 v 两个值中一个被测量，则通过式（5）我们可以估算出另一个值。例如，我们从式（5）估算得到镭C放出的 α 粒子的射程为4 cm，这很好地符合了卢瑟福后来得到的数值，而由该公式得到很短存活产物镭C'的寿命（ 10^{-3} 秒）与最近雅克布森的测量值也符合得很好。

英文

有趣的是我们还注意到，公式（5）也完全适用于较轻元素。根据（5）式，从钷放出的 α 粒子的速度可估算出钷的寿命约为 10^{12} 年，与观测值非常一致。

英文

在 α 衰变过程中，衰变的产物的原子核通常总是处于激发态的，它对应于具有较小能量的 α 粒子群的发射（ α 射线的精细结构）。这个公式有助于我们理解这类 α 粒子群的相对强度，也允许我们确认核的不同激发能级的量子数。另一方面，这个公式也解释了少量的所谓长程 α 粒子群对应于激发态核的衰变。

英文

与 α 衰变理论相比较，理解 β 衰变过程存在严重的困难。首先， β 衰变发射的电子具有连续的能量分布，这似乎与能量守恒定律相矛盾。玻

尔曾指出，由于现代量子理论不适用于涉及核电子的过程，因此，能量守恒定律并不适用于该过程。但正如朗道所指出的，在广义引力理论中，某个闭合曲面中的质量完全是用该曲面上的重力场来定义的，违反能量守恒定律在广义引力理论中将会遇到非常严重的困难。泡利提出，我们可以通过引入称之为“中微子”的一类新粒子来保证能量守恒定律。这些中微子没有电荷，只有很小（甚至趋于零）的质量，实际上在所有的实验中都没有观测到它，但很可能就是它带走了 β 衰变多余的能量。但是，这类粒子存在与否目前尚存在争议。 [英文](#)

最近，费米尝试在狄拉克相对论波动方程的基础上构建一套 β 衰变的理论，类比原子的光量子发射方式来处理原子核的电子发射。在该理论中，人们接受这种观点，即原子核的一个中子转变成一个质子，伴随产生了一个电子和一个中微子，它们一旦产生就会离开原子核，并将这个转变过程中释放的能量在它们之间分配。对导致这类转变的相互作用，能量采用某个确定值（约为 10^{-14} erg的量级），费米由此得到了 β 衰变元素合理的衰变常数的值，并与萨金特得到的 β 粒子的衰变常数和最大能量的关系曲线吻合得很好。 [英文](#)

然而，费米这套理论的一个有趣的结果是对 β 衰变给出了确定的不相容定则，这个结果是非常普遍的，适用于任何理论，即把电子发射认为是中子转变成质子的结果。按照这一定则，最初的原子核和产生具有不同自旋的那些原子核的 β 衰变过程并不都是允许的，且只能以较小的概率（约为自旋不变转变概率的百分之一）发生。这立即解释了由萨金特获得的两条不同的曲线正是分别对应于允许转变和不允许转变。伽莫夫已指出，将上述的 β 衰变的不相容定则应用于分析放射族得到了很好的结果，并且允许我们给出放射性核正常态和激发态确定的自旋值。

[英文](#)

（沈乃澂 翻译；张焕乔 审稿）

* 从等式 $n = p + \bar{e} + \Delta M_n c^2$ 和 $p = n + e + \Delta M_p c^2$ 中，我们可得到 $\Delta M_n c^2 - (-\Delta M_p c^2) = \Delta M_n c^2 + \Delta M_p c^2 = \bar{e} + e = 2mc^2 = 1.6 \times 10^{-6}$ erg。在图1中由纵坐标上的一个约0.016单位稳定宽度范围所反映。

Radioactivity Induced by Neutron Bombardment

E. Fermi

The impact of neutrons could induce radioactivity in many nuclei, as Enrico Fermi here reports. In experiments, he and colleagues had exposed a number of different elements to a source of neutrons, and found that in almost every case the exposed substances became radioactive. They found particularly strong effects with phosphorus, aluminium, silver, iodine and chromium, and measured half-lives varying from a few seconds to several hours. Fermi notes that it seemed likely nuclei were absorbing neutrons, which later transform into protons with ejection of an electron, thereby returning the nucleus to stability. Although very indirectly, these experiments hinted at the possibility of sustained nuclear reactions. [中文](#)

EXPERIMENTS have been carried out to ascertain whether neutron bombardment can produce an induced radioactivity, giving rise to unstable products which disintegrate with emission of β -particles. Preliminary results have been communicated in a letter to *La Ricerca Scientifica*, 5, 282; 1934. [中文](#)

The source of neutrons is a sealed glass tube containing radium emanation and beryllium powder. The amount of radium emanation available varied in the different experiments from 30 to 630

millicuries. We are much indebted to Prof. G. C. Trabacchi, Laboratorio Fisico della Sanità Pubblica, for putting at our disposal such strong sources. [中文](#)

The elements, or in some cases compounds containing them, were used in the form of small cylinders. After irradiation with the source for a period which varied from a few minutes to several hours, they were put around a Geiger counter with walls of thin aluminium foil (about 0.2 mm. thickness) and the number of impulses per minute was registered. [中文](#)

So far, we have obtained an effect with the following elements:

Phosphorus—Strong effect. Half-period about 3 hours. The disintegration electrons could be photographed in the Wilson chamber. Chemical separation of the active product showed that the unstable element formed under the bombardment is probably silicon.

Iron—Period about 2 hours. As the result of chemical separation of the active product, this is probably manganese.

Silicon—Very strong effect. Period about 3 minutes. Electrons photographed in the Wilson chamber.

Aluminium—Strong effect. Period about 12 minutes. Electrons photographed in the Wilson chamber.

Chlorine—Gives an effect with a period much longer than that of any element investigated at present.

Vanadium—Period about 5 minutes.

Copper—Effect rather small. Period about 6 minutes.

Arsenic—Period about two days.

Silver—Strong effect. Period about 2 minutes.

Tellurium—Period about 1 hour.

Iodine—Intense effect. Period about 30 minutes.

Chromium—Intense effect. Period about 6 minutes. Electrons photographed in the Wilson chamber.

Barium—Small effect. Period about 2 minutes.

Fluorine—Period about 10 seconds. [中文](#)

The following elements have also given indication of an effect: sodium, magnesium, titanium, zirconium, zinc, strontium, antimony, selenium and bromine. Some elements give indication of having two or more periods, which may be partly due to several isotopic constituents and partly to successive radioactive transformations. The experiments are being continued in order to verify these results and to extend the research to other elements. [中文](#)

The nuclear reaction which causes these phenomena may be different in different cases. The chemical separation effected in the cases of iron and phosphorus seems to indicate that, at least in these two cases, the neutron is absorbed and a proton emitted. The unstable product, by the emission of a β -particle, returns to the original element. [中文](#)

The chemical separations have been carried out by Dr. O. D'Agostino. Dr. E. Amaldi and Dr. E. Segrè have collaborated in the physical research. [中文](#)

(133, 757; 1934)

Enrico Fermi: Physical Institute, Royal University, Rome, April 10.

由中子轰击引发的放射性

费米

就像恩里科·费米在这篇文章中报道的一样，中子的碰撞会使许多原子核产生放射性。在实验中，他和其合作者们将许多种不同的元素暴露于中子源的辐射之下，发现几乎每一种实验中暴露的材料都会具有放射活性。并且他们在磷、铝、银、碘和铬中观察到了尤为强的效应，并测量得到它们的半衰期在数秒到几个小时之间不等。费米注意到似乎是原子核吸收了中子，并释放了一个电子，进而转变为质子，然后使原子核趋于稳定。这些实验尽管非常间接，但却隐含了持续核反应发生的可能性。 [英文](#)

为查明物质在中子的轰击下是否会产生感生放射性的实验已经完成了，该实验产生不稳定的产物，而该产物将继续发生蜕变并放射出 β 粒子。初步的结果发表在1934年《科学研究》杂志第5卷第282页的通讯中。 [英文](#)

中子源是一个密封的内含氡和铍粉末的玻璃管，在不同实验中，氡的用量从30到630毫居里不等。我们非常感谢公共卫生物理实验室的特拉巴基教授，他为我们提供了如此强的中子放射源。 [英文](#)

把某些元素或含有这些元素的化合物压制成小的圆柱体形状，用放射源辐照其数分钟到几个小时不等，之后将它们放在以薄铝箔（厚约0.2 mm）为壁的盖革计数器周围，并记录每分钟的脉冲数。 [英文](#)

迄今为止，我们已获得了下列元素在中子轰击下所产生的效应：

磷——强效应。半衰期约3小时。由磷物质蜕变放射出的电子可在威尔逊云室中被拍摄到。对放射性产物的化学分离情况显示，在中子的

轰击下产生的不稳定元素可能是硅。

铁——半衰期约2小时。根据对其放射性产物进行化学分离的结果分析，产生的元素可能是锰。

硅——非常强的效应。半衰期约3分钟。经辐照后产生的电子可在威尔逊云室中被拍摄到。

铝——强效应。半衰期约12分钟。经辐照后产生的电子可在威尔逊云室中被拍摄到。

氯——产生效应的周期比目前研究过的任何元素产生效应的周期都要长得多。

钒——半衰期约5分钟。

铜——效应很小。半衰期约6分钟。

砷——半衰期约2天。

银——强效应。半衰期约2分钟。

碲——半衰期约1小时。

碘——超强效应。半衰期约30分钟。

铬——超强效应。半衰期约6分钟。产生的电子可在威尔逊云室中被拍摄到。

钡——效应小。半衰期约2分钟。

氟——半衰期约10秒钟。 [英文](#)

下列元素也显示出存在效应的迹象：钠、镁、钛、锆、锌、锶、锑、硒和溴。其中有些元素显示出两个或多个半衰期，这可能是由于某些元素存在多种同位素，也可能是由于某些元素发生了连续的放射性衰变。为了验证以上这些实验结果并将该研究拓展到其他元素，相关实验仍在继续进行中。 [英文](#)

由上述实验现象所引起的核反应在不同情况下可能是不同的。铁和磷这两种元素的化学分离效应似乎表明，至少在中子轰击这两种元素时，原子核吸收了中子并放射出一个质子。在中子轰击下产生的不稳定产物通过放射出一个 β 粒子又转变为初始的元素。 [英文](#)

化学分离的工作由达戈斯蒂诺博士完成。阿马尔迪博士和塞格雷博士合作进行了物理方面的研究。 [英文](#)

（沈乃澂 翻译；夏海鸿 审稿）

Production of Large Quantities of Heavy Water

L. Tronstad

Nature had recently reported on the establishment of a British plant for the manufacture of heavy water. Here Leif Tronstad of the Institute of Inorganic Chemistry in Norway tells of a similar project already undertaken by the Norwegians. Large quantities of heavy water were being produced from a facility run by Norsk Hydro near Rjukan in the Telemark region. In principle, this facility could produce up to 10 litres of heavy water in a single day, if this came to be demanded by increasing research activity in physics, chemistry and biology. The plant was sabotaged by the Norwegian resistance during the Second World War to prevent heavy water being used to develop a German atomic bomb. [中文](#)

FROM the discussion recently held in the Royal Society¹, and from several communications on heavy hydrogen published in *Nature*, it is obvious that larger quantities of heavy water are at present much needed for investigations in several branches of physics, chemistry and biology. To meet this demand, Imperial Chemical Industries, Ltd., is to undertake commercial production at Billingham². It may also be of interest to report in this connexion, that various concentrates of the new water are now produced on a large scale in Norway by Norsk Hydro-Elektrisk Kvaelstofaktieselskab, Oslo. Large quantities of

“1:300-water” can be obtained from the above company, and richer concentrates will be available at a later date. 中文

This company at its works in Rjukan has one of the largest electrolytic hydrogen plants of the world, with a capacity of about 20,000 m.³ per hour. Assuming the efficiency of separation by electrolysis so low as 10 percent³, a quantity of about 10 litres of “pure” heavy water a day can be produced if the consumption requires. 中文

In full agreement with other investigators, it has been found that the efficiency is only slightly affected by the conditions of the electrolysis^{1,4}. However, certain difficulties arose using sulphuric acid with lead electrodes, due to the formation of porous lead on the cathodes and to the formation of fog. The efficiency of separation in both acid and alkaline solution agree fairly well with that found, for example, by Harteck⁵. Further details of the experimental results are to be published shortly in the *Zeitschrift für Elektrochemie*. 中文

(133, 872; 1934)

Leif Tronstad: Institute of Inorganic Chemistry, Norwegian Technical High School, Trondhjem, Norway, May, 4.

References:

1. *Proc. Roy. Soc., A*, **144**, 1; 1934.
2. *Nature*, **133**, 604, April 21, 1934.
3. Taylor, Eyring and Frost, *J. Chem. Phys.*, **1**, 823; (1933).
4. Compare, for example, Topley and Eyring, *Nature*, **133**, 292, Feb. 24, 1934. Bell and Wolfenden, *ibid.*, p.25.
5. Harteck, *Proc. Roy. Soc.*, loc. cit. and *Proc. Phys. Soc.*, **40**, 277; 1934.

重水的大量生产

特龙斯塔

《自然》最近对一个生产重水的英国工厂进行了报道。这篇文章中挪威无机化学研究所的莱夫·特龙斯塔指出，由挪威人承担的一个类似的项目已经启动了。大量的重水正在由泰勒马克行政区留坎附近挪威海德鲁公司运营的装置生产出来。原则上，这一装置每天可以生产多达10升的重水，以满足日益增长的物理学、化学和生物学研究的需求。这一工厂在第二次世界大战期间曾被挪威抵抗组织破坏，以防止重水被德国用来研制原子弹。 [英文](#)

根据皇家学会近期举办的有关重氢的讨论会^[1]以及在《自然》上发表的几篇关于重氢的通讯，我们可以明显地感觉到，目前在物理学、化学和生物学若干分支的科学研究中对重水有很大的需求。为了满足这种需求，帝国化学工业有限公司在比林罕进行了商业化生产^[2]。目前挪威奥斯陆的挪威水电气有限公司（即现在的挪威海德鲁公司）大规模生产各种新水的浓缩物，对此进行报道也有可能引起人们的兴趣。从上述公司可以得到大量的“1:300的水”，今后将可以获得浓度更高的浓缩物。

[英文](#)

这家公司在留坎的制造厂拥有一个全球最大的电解氢工厂，其产量约为每小时20,000立方米。假定通过电解分离的效率只有10%^[3]，如果有消费需求，每天大约可以生产10升“纯净的”重水。 [英文](#)

已经发现电解条件对其效率仅有轻微的影响^[1,4]，这与其他研究者的结果完全一致。然而，由于会形成雾气以及在阴极上会形成多铅孔，在硫酸与铅电极一起使用的过程中出现了某些困难。正如哈特克^[5]的发现，酸溶液和碱溶液两者的分离效率与上述发现非常一致。对实验结果更加详细的说明将于近期发表在《电化学杂志》上。 [英文](#)

(沈乃澍 翻译；李芝芬 审稿)

Possible Production of Elements of Atomic Number Higher than 92

E. Fermi

Physicists bombarding matter with charged particles had for the most part achieved induced radioactivity only with fairly light elements, because it was hard to reach the energies required to achieve an effect with heavier elements. But as Fermi here points out, this limitation did not apply to neutrons, which he had recently shown could induce radioactivity in a wide range of elements. Fermi describes new experiments with heavy elements, especially uranium. The resulting radiation showed half-lives from 10 seconds up to around 40 minutes. Experiments had ruled out the formation of isotopes of uranium, palladium, thorium, actinium, radium, bismuth and lead. The resulting radioactive isotope apparently had atomic number higher than 92, the maximum then known for any element. [中文](#)

UNTIL recently it was generally admitted that an atom resulting from artificial disintegration should normally correspond to a stable isotope. M. and Mme. Joliot first found evidence that it is not necessarily so; in some cases the product atom may be radioactive with a measurable mean life, and go over to a stable form only after emission of a positron. [中文](#)

The number of elements which can be activated either by the impact of an α -particle (Joliot) or a proton (Cockcroft, Gilbert, Walton) or a deuteron (Crane, Lauritsen, Henderson, Livingston, Lawrence) is necessarily limited by the fact that only light elements can be disintegrated, owing to the Coulomb repulsion. [中文](#)

This limitation is not effective in the case of neutron bombardment. The high efficiency of these particles in producing disintegrations compensates fairly for the weakness of available neutron sources as compared with α -particle or proton sources. As a matter of fact, it has been shown¹ that a large number of elements (47 out of 68 examined until now) of any atomic weight could be activated, using neutron sources consisting of a small glass tube filled with beryllium powder and radon up to 800 millicuries. This source gives a yield of about one million neutrons per second. [中文](#)

All the elements activated by this method with intensity large enough for a magnetic analysis of the sign of the charge of the emitted particles were found to give out only negative electrons. This is theoretically understandable, as the absorption of the bombarding neutron produces an excess in the number of neutrons present inside the nucleus; a stable state is therefore reached generally through transformation of a neutron into a proton, which is connected to the emission of a β -particle. [中文](#)

In several cases it was possible to carry out a chemical separation of the β -active element, following the usual technique of adding to the irradiated substance small amounts of the neighbouring elements. These elements are then separated by chemical analysis and separately checked for the β -activity with a Geiger-Müller counter. The activity always followed completely a certain element, with which the active element could thus be identified. [中文](#)

In three cases (aluminium, chlorine, cobalt) the active element formed

by bombarding the element of atomic number Z has atomic number $Z-2$. In four cases (phosphorus, sulphur, iron, zinc) the atomic number of the active product is $Z-1$. In two cases (bromine, iodine) the active element is an isotope of the bombarded element. 中文

This evidence seems to show that three main processes are possible: (a) capture of a neutron with instantaneous emission of an α -particle; (b) capture of the neutron with emission of a proton; (c) capture of the neutron with emission of a γ -quantum, to get rid of the surplus energy. From a theoretical point of view, the probability of processes (a) and (b) depends very largely on the energy of the emitted α - or H-particle; the more so the higher the atomic weight of the element. The probability of process (c) can be evaluated only very roughly in the present state of nuclear theory; nevertheless, it would appear to be smaller than the observed value by a factor 100 or 1,000. 中文

It seemed worth while to direct particular attention to the heavy radioactive elements thorium and uranium, as the general instability of nuclei in this range of atomic weight might give rise to successive transformations. For this reason an investigation of these elements was undertaken by the writer in collaboration with F. Rasetti and O. D'Agostino. 中文

Experiment showed that both elements, previously freed of ordinary active impurities, can be strongly activated by neutron bombardment. The initial induced activity corresponded in our experiments to about 1,000 impulses per minute in a Geiger counter made of aluminium foil of 0.2 mm. thickness. The curves of decay of these activities show that the phenomenon is rather complex. A rough survey of thorium activity showed in this element at least two periods. 中文

Better investigated is the case of uranium; the existence of periods of about 10 sec., 40 sec., 13 min., plus at least two more periods from 40 minutes to one day is well established. The large uncertainty in the

decay curves due to the statistical fluctuations makes it very difficult to establish whether these periods represent successive or alternative processes of disintegration. 中文

Attempts have been made to identify chemically the β -active element with the period of 13 min. The general scheme of this research consisted in adding to the irradiated substance (uranium nitrate in concentrated solution, purified of its decay products) such an amount of an ordinary β -active element as to give some hundred impulses per minute on the counter. Should it be possible to prove that the induced activity, recognisable by its characteristic period, can be chemically separated from the added activity, it is reasonable to assume that the two activities are not due to isotopes. 中文

The following reaction enables one to separate the 13 min.-product from most of the heaviest elements. The irradiated uranium solution is diluted in 50 percent nitric acid; a small amount of a manganese salt is added and then the manganese is precipitated as dioxide (MnO_2) from the boiling solution by addition of sodium chlorate. The manganese dioxide precipitate carries a large percentage of the activity. 中文

This reaction proves at once that the 13 min.-activity is not isotopic with uranium. For testing the possibility that it might be due to an element 90 (thorium) or 91 (palladium), we repeated the reaction at least ten times, adding an amount of uranium $X_1 + X_2$ corresponding to about 2,000 impulses per minute; also some cerium and lanthanum were added in order to sustain uranium X. In these conditions the manganese reaction carried only the 13 min.-activity; no trace of the 2,000 impulses of uranium X_1 (period 24 days) was found in the precipitate; and none of uranium X_2 , although the operation had been performed in less than two minutes from the precipitation of the manganese dioxide, so that several hundreds of impulses of uranium X_2 (period 75 sec.) would have been easily recognisable. 中文

Similar evidence was obtained for excluding atomic numbers 88 (radium) and 89 (actinium). For this, mesothorium-1 and -2 were used, adding barium and lanthanum; the evidence was completely negative, as in the former case. The eventual precipitation of uranium- X_1 and mesothorium-1, which do not emit β -rays penetrating enough to be detectable in our counters, would have been revealed by the subsequent formation respectively of uranium- X_2 and mesothorium-2.

中文

Lastly, we added to the irradiated uranium solution some inactive lead and bismuth, and proved that the conditions of the manganese dioxide reaction could be regulated in such a way as to obtain the precipitation of manganese dioxide with the 13 min.-activity, without carrying down lead and bismuth.

中文

In this way it appears that we have excluded the possibility that the 13 min.-activity is due to isotopes of uranium (92), palladium (91), thorium (90), actinium (89), radium (88), bismuth (83), lead (82). Its behaviour excludes also ekacaesium (87) and emanation (86).

中文

This negative evidence about the identity of the 13 min.-activity from a large number of heavy elements suggests the possibility that the atomic number of the element may be greater than 92. If it were an element 93, it would be chemically homologous with manganese and rhenium. This hypothesis is supported to some extent also by the observed fact that the 13 min.-activity is carried down by a precipitate of rhenium sulphide insoluble in hydrochloric acid. However, as several elements are easily precipitated in this form, this evidence cannot be considered as very strong.

中文

The possibility of an atomic number 94 or 95 is not easy to distinguish from the former, as the chemical properties are probably rather similar. Valuable information on the processes involved could be

gathered by an investigation of the possible emission of heavy particles. A careful search for such heavy particles has not yet been carried out, as they require for their observation that the active product should be in the form of a very thin layer. It seems therefore at present premature to form any definite hypothesis on the chain of disintegrations involved. [中文](#)

(133, 898-899; 1934)

E. Fermi: Royal University of Rome.

Reference:

1. E. Fermi, *Ricerca Scientifica*, **1**, 5, 283; 6, 330. *Nature*, **133**, 757, May 19, 1934. E. Amaldi, O. D'Agostino, E. Fermi, F. Rasetti, E. Segrè, *Ricerca Scientifica*, **8**, 452; 1934.

原子序数大于92的元素的可能生成

费米

物理学家使用带电粒子对物质进行轰击，大部分情况下会产生感生放射性，而这仅仅是对于轻元素而言的，因为很难获得足以对重元素产生效应的能量。但费米在这篇文章中指出，使用中子进行轰击时不受此限制，他最近的研究表明中子可以使更大范围内的元素产生感生放射性。费米在本文中描述了关于重元素尤其是铀的新实验。得到的放射性元素的半衰期从10秒至40分钟左右不等。该实验排除了产生铀、镤、钍、镭、镭、铀和铅的同位素的可能。得到的放射性同位素的原子序数明显大于92，这是当时已知的最大的原子序数。 [英文](#)

人工嬗变得到的原子总是对应于一个稳定同位素，这一观点直到现在仍被广泛认可。但是约里奥夫妇首次通过实验结果证实事实并不完全是这样；在某些情况下，产生的原子具有放射性并具有可测量的平均寿命，且只有在放射出一个正电子之后它才达到稳定的状态。 [英文](#)

由于库仑斥力的存在，只有轻元素可以发生嬗变，因此不论是用 α 粒子（约里奥）、质子（考克饶夫、吉尔伯特、瓦耳顿）还是用氘（克兰、劳里森、亨德森、利文斯通、劳伦斯）来轰击，可以被活化的元素的数目都必然要受到上述事实的限制。 [英文](#)

但是在用中子轰击的情况下，这样的限制就失效了。中子引发蜕变的高效性完全弥补了中子源相对 α 粒子源或质子源较弱的缺点。事实上，不论原子量的大小，许多元素（截至目前试验过的68种元素中的47种）都可以被一个由铍粉和辐射剂量为800毫居里的氡填充的小玻璃管构成的中子源所活化^[1]。这个中子源每秒释放出大约一百万个中子。

[英文](#)

用这种方法活化的元素，其放射性强度强到足以通过磁学手段去分析放射出的粒子所携带的电荷符号，我们通过观察发现这些元素只能放出负电性的电子。这一点在理论上是可以理解的，由于轰击的中子被吸收而使核内的中子数增加；而只有当一个中子转变为一个质子时，体系才会达到稳定态，这个过程还会相应地放射出一个 β 粒子。 [英文](#)

在某些情况下，利用通常采用的加入少量相邻元素的技术，可以对具有 β 放射性的元素进行化学分离。然后通过化学分析的手段将这些元素分离，并用盖革-米勒计数器分别检验它们的 β 放射性。这种放射性通常伴随着一个完全确定的元素，通过这个元素可以确定具有放射性的元素。 [英文](#)

在三种情况下（铝、氯、钴），轰击原子序数为 Z 的元素会形成原子序数为 $Z-2$ 的放射性元素。在四种情况下（磷、硫、铁、锌），放射性产物的原子序数为 $Z-1$ 。在两种情况下（溴、碘），产生的放射性元素是被轰击元素的一种同位素。 [英文](#)

上述证据似乎表明，可能有三种主要过程：（ a ）俘获一个中子，即时放出一个 α 粒子；（ b ）俘获一个中子，放出一个质子；（ c ）俘获一个中子，放出一个 γ 量子，以带走过剩的能量。从理论上讲，过程（ a ）和（ b ）发生的概率主要依赖于放出的 α 粒子或 H 粒子的能量；元素的原子量越大，依赖程度越强。根据目前的核理论，我们只能对过程（ c ）发生的概率做出很粗略的估计；然而，这个估计值是观测值的1/1,000或1/100。 [英文](#)

对于放射性重元素钍和铀给予特别的关注似乎是必要的，因为在这个原子量的范围内，原子核普遍的不稳定性会引发一系列的元素间的变换。基于这个原因，笔者与拉塞蒂和达戈斯蒂诺合作对这些元素进行了相关研究。 [英文](#)

实验表明，在除去常见的放射性杂质之后，这两种元素都可以在中子轰击下被强烈活化。在我们实验中，使用盖革计数器对初始阶段感生放射性的强度的测量结果为每分钟约1,000个脉冲，这个计数器用0.2毫米厚的铝箔制得。这种放射性的衰减曲线表明这种现象是相当复杂的。对钍元素放射性的粗略观测表明，在这个元素的感生放射性的衰减过程

中至少有两个周期。 [英文](#)

铀得到了更好的研究；已经确定存在的周期包括10秒、40秒和13分钟，还包括介于40分钟到1天之间的至少两个以上的周期。统计涨落导致衰减曲线具有很大的不确定性，这使得人们难以确定这些周期是代表链式反应的衰变过程还是代表并行反应的衰变过程。 [英文](#)

我们尝试对周期为13分钟的 β 放射性元素进行化学识别。这项研究的总体方案是向被辐照的物质（除去了衰变产物的硝酸铀的浓溶液）中加入一定量的普通 β 放射性元素，使得它们在计数器中给出每分钟几百个脉冲的计数。通过其特征周期可以对感生放射性成分进行辨认，而如果感生放射性成分可以与加入的放射性成分进行化学分离的话，那么就可以合理地认定这两类放射性并不是源于多种同位素。 [英文](#)

下面的反应能使我们能够将周期为13分钟的产物与大多数最重的元素分离开。将被辐照的铀溶液用50%的硝酸稀释；加入少量的锰盐，在沸腾的溶液中加入氯酸钠使锰以二氧化物（二氧化锰）的形式沉淀出来。二氧化锰沉淀物携带了大部分的放射性。 [英文](#)

这个反应同时也证明了周期为13分钟的放射性物质不是铀的同位素。为了验证该放射性是否来源于90号元素（钷）或91号元素（镨），我们至少重复了10次这个反应，加上适量的铀-X₁和铀-X₂，它们的放射性强度相当于每分钟约2,000个脉冲；为了稳定住铀-X还加入了一些钷和镧。在这样的条件下，锰的反应只会携带周期为13分钟的放射性；尽管我们将测量过程控制在二氧化锰沉淀产生后2分钟之内完成，因为这样的条件下源自铀-X₂（周期75秒）的几百个脉冲应该是很容易检测到的，但我们在沉淀物中没有追踪到源自铀-X₁（周期24天）的2,000个脉冲，也没有发现铀-X₂的脉冲。 [英文](#)

利用类似的证据我们排除了原子序数为88（镭）和89（锕）的元素的可能性。在实验中，我们使用了新钷-1和新钷-2，并加入了钷和镧；与前述情况类似，证据完全是否定性的。铀-X₁和新钷-1的最终沉淀物原被解释为分别生成了铀-X₂和新钷-2，但实验中我们的计数器并未探测到 β 射线。 [英文](#)

最后，我们向经辐照的铀溶液加入一些非放射性的铅和铋，这证明了二氧化锰沉淀反应的条件可以通过这种方法进行调整，从而得到具有周期为13分钟的放射性二氧化锰沉淀，且不含有铅和铋。 [英文](#)

通过这样的方法，我们已排除了周期为13分钟的放射性是源于铀的同位素（92）、镤（91）、钍（90）、镭（89）、锕（88）、铋（83）和铅（82）的可能性，其行为也排除了钷（87）和钷（86）的可能性。 [英文](#)

周期为13分钟的放射性可能来自一系列重元素的否定性证据，为我们指出了另一种可能性，即该放射性元素的原子序数可能大于92。如果它是93号元素，那么它将与镤和镭同族。这个假设在某种程度上得到了以下观测事实的支持，即周期为13分钟的放射性可以随不溶于盐酸的硫化镭沉淀而出。然而，由于还有其他一些元素也很容易以这种形式产生沉淀，因此，我们不能认定其为一种强有力的证据。 [英文](#)

该元素原子序数为94或95的可能性很难与前述可能性相区分，因为它们的化学性质可能相当类似。此过程中包含的有价值的信息可以通过研究可能存在的重粒子发射行为而获得。不过对这类重粒子的仔细探索尚未展开，因为它们需要在薄层形式的放射性产物中进行观测。因此在目前情况下，我们还不能对所涉及的衰变链做出任何确定的假设。

[英文](#)

（沈乃澂 翻译；朱永生 审稿）

The Factor $\frac{137}{136}$ in Quantum Theory

A. S. Eddington

Arthur Eddington developed speculative theories to account for the values of the fine structure constant (which determines the strength of electrical forces) and the mass ratio of the proton to electron. In his theory these values were exactly $1/137$ and 1847.6 , in good agreement with experiments. But the measured ratio of electron charge to mass was slightly smaller than predicted, by a factor of more or less precisely $136/137$. Here Eddington tries to explain how this extra factor might arise from the indistinguishability of electrons, which could cause overestimation of the electron mass by a factor of $137/136$. Eddington's speculations did not stand the test of time, but reflected a preoccupation with finding simplicities among the known fundamental constants. [中文](#)

IT has been suggested by W. N. Bond¹ that, in some or all of the attempts to determine e/m experimentally, the quantity actually found is $\frac{136}{137}e/m$; for if the experimental results are corrected in accordance with this hypothesis, they are found to be in satisfactory accordance with my theoretical values of the fine-structure constant (137) and mass-ratio (1847.6). R. T. Birge² has confirmed this; and, quoting three important recent determinations of e/m , he has shown that the agreement is extremely close. [中文](#)

On theoretical grounds it seems likely that Bond's hypothesis is right. In my earliest paper on the subject³, I gave the value of the fine-structure constant as 136 , since I found the Coulomb energy of two elementary particles to be $1/136r$ in natural quantum units. This energy was $\frac{137}{136}$ times too large, because I had not allowed for the 137th degree of freedom arising from the indistinguishability of the particles. Bond's hypothesis implies that I am not the only victim of this mistake; current quantum theory in deriving from observational data the proper-energy or mass m of an electron has also obtained an energy $\frac{137}{136}$ times too large. If so, the cause is presumably the same, namely, neglect to take into account the degree of freedom due to indistinguishability. 中文

There is nothing mystical in the effect of indistinguishability. It occasions, not an objective difference of behaviour, but a difference in what we can ascertain about the behaviour, and hence a difference of treatment. In the dynamics of two particles, we have to describe the change with time of the positions, momenta and spin-components (or of a probability distribution of them) of the particles which we call No.1 and No.2; and also we have to describe a growing uncertainty whether the particle, called No.1 at the time t , is the original No.1. If the probability that it is the original No.1 is $\cos^2\theta$ (so that the probability that it is the original No. 2 is $\sin^2\theta$) the permutation variable θ will be a function of the time and have all the properties of a dynamical variable, giving therefore an extra degree of freedom of the system and having a momentum (energy of interchange) associated with it. When, however, the particles are distinguished without uncertainty, θ is constrained to be zero, and this degree of freedom is lost. 中文

Thus for the treatment of two indistinguishable particles, we have to start with an a priori probability distributed over a closed domain of 137 dimensions, whereas for two distinguishable particles it is

distributed over a closed domain of 136 dimensions. Naturally, the average values of characteristics of the distribution are slightly different in the two treatments. In particular, the energy tensor of the a priori probability distribution, which is identical with the metrical tensor $g_{\mu\nu}$ of macroscopic theory, is different. Hence *the two kinds of treatment are associated with different metrics of space-time*. It seems clear that a factor $\frac{137}{136}$ (neglected in current quantum theory) will be introduced by the change of metric when we equate the space occupied by the indistinguishable particles of quantum theory to the space occupied by the distinguishable parts of our measuring apparatus. 中文

It may be asked: Why does this factor affect the mass of the electron but not that of the proton? The discrimination is, I think, not strictly between the proton and electron, but between the resultant mass ($M + m$) which is nearly the mass of a proton, and the reduced mass of the relative motion $Mm/(M + m)$ which is nearly the mass of an electron; for it is in the relative motion that the question of distinguishing the two ends of the relation arises. It may also be asked why the factor $\frac{137}{136}$, which refers especially to a system of two particles, applies irrespective of the number of particles. The answer is that the metrical ideas of quantum theory are borrowed from those of relativity theory; and since the latter are based on the interval between two points, the former refer correspondingly to the wave function of two particles. 中文

(133, 907; 1934)

A. S. Eddington: Observatory, Cambridge, June 5.

References:

1. W. N. Bond, *Nature*, **133**, 327, March 3, 1934.
2. R.T. Birge, *Nature*, **133**, 648, April 28, 1934.
3. A. S. Eddington, *Proc. Roy. Soc., A*, **122**, 358; 1929.

量子理论中的137/136因子

爱丁顿

阿瑟·爱丁顿发展了一套推测性的理论，用来说明精细结构常数（其决定了电场力的强度）以及质子与电子的质量比的重要性。在爱丁顿的理论中，以上两个值与实验结果很好地吻合，分别严格等于 $1/137$ 和 1847.6 。但测量得到的电子荷质比略小于理论预期值，相差了大约 $136/137$ 这个因子。本文中爱丁顿试图用电子的不可分辨性来解释这个多出来的因子，正是电子的不可分辨性导致估算得到的电子质量是实值的 $137/136$ 倍。爱丁顿的假设虽然没有经得住时间的考验，但这反映出他当时专注于在已知的基本常数中寻求简单性。 [英文](#)

邦德^[1]提出，在某些或者说全部试图测定荷质比 e/m 值的实验中得到的结果都是真实的荷质比 e/m 值的 $136/137$ ；如果实验结果按此假设进行修正，则其与我从理论计算得到的精细结构常数（ 137 ）以及质子与电子的质量比（ 1847.6 ）的值是完全吻合的。伯奇^[2]已经证实了这个结论；他引用了三次最近对荷质比 e/m 的重要测量，表明这些结果都是非常一致的。 [英文](#)

在理论计算的基础上，邦德的假设看起来似乎是正确的。我在关于这方面研究的早期文章中^[3]给出了精细结构常数的值为 136 ，因为我发现两个基本粒子的库仑能量可以用自然量子单位表示成 $1/136r$ 。事实上，我所得到的这个能量值相对而言远大于真实的结果，是真实值的 $137/136$ 倍，原因是我没有考虑与粒子的不可分辨性相对应的第 137 个自由度。邦德的假设表明，我并不是这个错误的唯一受害者；目前的量子理论从观测数据得到电子的固有能量或质量 m 的结果表明，观测得到的结果也远大于真实值，是真实值的 $137/136$ 倍。如果事实确实如此，

则原因估计是相同的，即都没有考虑到与粒子的不可分辨性相对应的自由度。 [英文](#)

粒子的不可分辨性本身并没有什么神秘之处。它不会使粒子的行为出现客观本质上的变化，而是引起了我们对粒子行为的主观推断的变化，进而使我们的处理方式有所不同。处理两个粒子的动力学行为时，我们必须给出这两个粒子的位置、动量和自旋分量随时间变化的情况（或者这些量的概率分布），我们把这两个粒子命名为1号粒子和2号粒子；另外，我们还必须考虑 t 时刻的1号粒子是否仍为原来的1号粒子这种不确定性的增长。如果 t 时刻的1号粒子是原来的1号粒子的概率是 $\cos^2\theta$ （因而是原来的2号粒子的概率便是 $\sin^2\theta$ ），则置换变量 θ 将是时间的函数，并具有力学量的所有性质，因此系统多了一个与动量（能量交换）相关的自由度。然而，如果不考虑不确定性，即粒子可分辨时， θ 值就只能为零，系统就没有这类自由度了。 [英文](#)

因此，在处理两个不可分辨的粒子时，我们在137维的闭域内利用先验的概率分布来处理问题；而对于两个可分辨的粒子的情况，则以136维的闭域内先验的概率分布为出发点。自然地，两类处理情况下的概率分布的平均特征值稍有差别。尤其是与宏观理论的度规张量 $g_{\mu\nu}$ 等价的先验概率分布的能量张量在这两种情况下是不同的。因此，两类处理是与时空的两个不同度规相关的。似乎很明显可见，当我们将量子理论中由不可分辨的粒子所占据的空间与由测量装置中可分辨的粒子所组成的空间视为等同时，由于两个空间度规的不同将引入137/136这个因子（在目前的量子理论中是忽略该因子的）。 [英文](#)

可能有人会问：为何这个因子会影响电子的质量，而不影响质子的质量？我认为以上的两种质量并不是严格的质子和电子的质量，而是合成质量 $(M+m)$ 与相对运动的约化质量 $Mm/(M+m)$ ，前者几乎是质子的质量，而后者几乎是电子的质量；正是由于考虑了相对运动，使得我们在辨别质量关系的两种极限时出现了问题。也许有人还会问，为何从两个粒子所组成的系统这一特殊情况中推出的因子137/136也适用于其他系统，而与组成系统的粒子数无关。原因是量子理论中度规的想法是借用相对论中度规的概念而来的；后者是基于两点之间的间隔，而前者与两个粒子的波函数有关。 [英文](#)

(沈乃澍 翻译；李军刚 审稿)

Exchange Forces between Neutrons and Protons, and Fermi's Theory

Ig. Tamm

Soviet physicist Igor Tamm, a pioneer in nuclear science and future Nobel laureate, here comments on Enrico Fermi's recent theory of beta radioactivity, which assumes that protons and neutrons can be transmuted into one another while emitting or absorbing electrons, positrons and neutrinos. As Tamm argues, Fermi's scheme suggests that the force binding nuclei might be an "exchange force" between nuclear particles, originating in the exchange of light particles in direct analogy to the photon-exchange process mediating the electromagnetic force. But a simple estimate of the magnitude of such a force yields a value that is far too small. Tamm's result implied that physicists were still seeking another fundamental force, which would later become known as the nuclear strong force. [中文](#)

FERMI¹ has recently developed a successful theory of β -radioactivity, based on the assumption that transmutations of a neutron into a proton and vice versa are possible and are accompanied by the birth or disappearance of an electron and a neutrino. [中文](#)

This theory implies the possibility of deducing the exchange forces between neutrons and protons, introduced more or less

phenomenologically by Heisenberg. (This idea occurred also quite independently to my friend, D. Iwanenko, with whom I have since had the opportunity of discussing the question.) Consider two heavy particles a and b , a being in a neutron and b in a proton state. If a becomes a proton and b a neutron the energy remains unchanged. Now these two degenerate states of the system may be linked up by a two-step process: the emission of an electron and a neutrino by the neutron a which becomes a proton, and the ensuing re-absorption of these light particles by the proton b which becomes a neutron. The energy of the system will be in general not conserved in the intermediate state (compare the theory of dispersion). The emission and re-absorption of a positron and neutrino may also take place². In this way the two degenerate states of the system considered are split into two energy states, differing by the sign of the exchange energy.

中文

Since the rôle of the light particles (ψ -field) providing an interaction between heavy particles corresponds exactly to the rôle of the photons (electromagnetic field), providing an interaction between electrons, we may adapt for our purposes the methods used in quantum electrodynamics to deduce the expression for Coulomb forces. 中

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Putting $\psi = \psi_0 + g\psi_1 + g^2\psi_2 + \dots$, where g is the Fermi constant ($\sim 4 \times 10^{-50}$ erg. cm.³), and using the theory of perturbations and retaining only that part of ψ which corresponds to the absence of light particles in the initial and final states, we obtain

$$\left(H_0 - i\hbar \frac{\partial}{\partial t}\right)\psi_2 \sim \left(K \mp \frac{1}{16\pi^3 \hbar c r^5} I(r)\right)\psi_0,$$

where K is an infinite constant, r is the distance between a and b and $I(r)$ is a decreasing function of r , which is equal to 1 when $r \ll \hbar/mc$ (m is the mass of the electron). Neglecting K , one would obtain the

same result if one introduced directly in the wave equation of the heavy particles an exchange energy $A(r)$:

$$A(r) = \pm \frac{g^2}{16\pi^3 \hbar c r^5} I(r),$$

the sign of $A(r)$ depending on the symmetry of ψ in respect to a and b . Introducing the values of $\hbar$, c and g , we obtain

$$|A(r)| \ll 10^{-5} r^{-5} \text{ erg.}$$

中文

Thus $A(r)$ is far too small to account for the known interaction of neutrons and protons at distances of the order of $r \sim 10^{-13}$ cm. 中

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If the difference of masses of the neutron and of the proton is larger than the sum of the masses of an electron and a neutrino, the emission of light particles by a heavy particle may take place without violation of the conservation of energy. But again the corresponding value of the exchange energy may be shown to be far too small

$$|A(r)| < g \left(\frac{mc}{\hbar} \right)^3 \sim 10^{-18} \text{ erg.}$$

中文

Our negative result indicates that either the Fermi theory needs substantial modification (no simple one seems to alter the results materially), or that the origin of the forces between neutrons and protons does not lie, as would appear from the original suggestion of Heisenberg, in their transmutations, considered in detail by Fermi.

中文

(133, 981; 1934)

References:

1. Fermi, Z. *Phys.*, **88**, 161; 1934.
2. Wick, *Rend. R. Nat. Acad. Lincei*, **19**, 319; 1934.

质子中子之间的交换力与费米理论

塔姆

苏联物理学家伊戈尔·塔姆是核科学界的先驱，并在之后获得了诺贝尔奖，这篇文章中他评论了恩里科·费米新近的 β 衰变理论，费米假定质子和中子可以相互转化，并在此过程中放出或者吸收电子、正电子和中微子。事实正如塔姆所质疑的那样，费米的理论方案表明束缚原子核的作用力可能是一种原子核粒子间的“交换作用”，这一想法源于对电磁相互作用中以光子交换过程为媒介的交换的直接类比，但是对于这种相互作用大小的粗略估算得到数值过小。塔姆的结果表明物理学家仍在寻找另一种基本相互作用，而这种相互作用后来被称为强相互作用。 [英文](#)

最近，费米^[1]成功地发展了一套关于 β 衰变的理论。这个理论基于这样的假设：中子转变为质子或质子转变为中子都是有可能的，并且在此过程中伴随着一个电子和一个中微子的产生或消失。 [英文](#)

这一理论意味着推导出质子和中子之间的交换力是有可能的，交换力这一概念在某种程度上是由海森堡唯象地引入的。（这个概念也曾独立地出现在我的朋友伊万年科的脑海中，我曾有机会和他讨论过这个问题。）设有两个重粒子 a 和 b ， a 处于中子态， b 处于质子态。如果 a 变成一个质子，而 b 变成一个中子，系统能量保持不变。这样，系统的这两个简并态就可以通过以下两个步骤联系起来：首先，中子 a 放出一个电子和一个中微子，变成一个质子；其次，质子 b 再吸收这些轻粒子，变成一个中子。整个系统的能量在中间态（与色散理论相比）并不守恒。正电子和中微子的发射和再吸收同样也有可能发生^[2]，因此以这种方法所考虑的系统的两个简并态就劈裂成交换能符号不同的两个能态。

[英文](#)

由于轻粒子（ ψ 场）在重粒子相互作用中所扮演的角色与光子（电磁场）在电子相互作用中所扮演的角色非常类似，所以，我们可以采取量子电动力学中推导库仑力表达式的方法来研究我们的问题。 [英文](#)

设 $\psi = \psi_0 + g\psi_1 + g^2\psi_2 + \dots$ ，其中 g 为费米常数（ $\sim 4 \times 10^{-50}$ 尔格·立方厘米），用微扰理论，且只保留初末态中与轻粒子的缺失有关的那部分 ψ ，可以得到：

$$\left(H_0 - i\hbar \frac{\partial}{\partial t}\right)\psi_2 \sim \left(K \mp \frac{1}{16\pi^3 \hbar c r^5} I(r)\right)\psi_0,$$

其中， K 是一个无限大的常数， r 表示 a 和 b 之间的距离， $I(r)$ 是 r 的单调下降函数，当 $r \ll \hbar/mc$ 时， $I(r)$ 等于 1（ m 是电子的质量）。不考虑常数 K ，如果将交换能 $A(r)$ 直接引入重粒子的波动方程，我们将会得到相同的结果。 $A(r)$ 的表达式为：

$$A(r) = \pm \frac{g^2}{16\pi^3 \hbar c r^5} I(r)$$

$A(r)$ 的符号取决于由 a 和 b 决定的 ψ 的对称性。将 $\hbar$ 、 c 和 g 的值代入上式，我们得到：

$$|A(r)| \ll 10^{-85} r^{-5} \text{ 尔格}$$

[英文](#)

因此，如果中子和质子的距离 $r \sim 10^{-13}$ 厘米量级，那么 $A(r)$ 的值就太小了，以致于无法解释中子和质子之间已知的相互作用。 [英文](#)

如果中子和质子之间的质量差大于电子和中微子的质量和，那么重粒子发射轻粒子的过程就可能不违反能量守恒原理，但是，相应的交换能的值仍然太小：

$$|A(r)| < g \left(\frac{mc}{\hbar} \right)^3 \sim 10^{-18} \text{ 尔格}$$

[英文](#)

我们得到的负面结果表明，不是费米理论需要根本的修正（因为使

结果有实质上的改变绝非易事），就是中子和质子之间作用力的源头根本不像海森堡最初设想，且由费米细致考虑的那样存在于它们的相互转变之中。 [英文](#)

（王静 翻译；王乃彦 审稿）

Interaction of Neutrons and Protons

D. Iwanenko

Russian physicist Dmitri Iwanenko here argues that Fermi's recent theory of beta radioactivity, while successful in some regards, makes some erroneous predictions. For decays observed in light nuclei, the theory gives a roughly correct link between the rate of decay and the maximum energy of the ejected particles. However, if one uses the theory to consider nuclear binding as an exchange of force-mediating particles similar to the electromagnetic force, one finds the force is only large enough at a distance between nucleons of about 10^{-17} m, which is far too small. Iwanenko concludes that Fermi's theory is thus only a very crude approximation.

[中文](#)

AS electrons and positrons are expelled in some reactions from nuclei, we can try to treat these *light* particles like the photons emitted by atoms. Then the interaction of *heavy* particles (protons, neutrons) can be considered as taking place *via* light particles described by the equations of a ψ -field in the same manner as electromagnetic, for example, Coulomb, interaction takes place through an electromagnetic field, or photons. [中文](#)

The *first* order effects are the expulsion (or absorption) of an electron, which case was treated recently by Fermi, or of a positron. We may

remark that the application of Fermi's formalism to positron disintegration of light nuclei (which we get by changing the sign of the charge number and taking for the latter the appropriate value) gives results which fit, though not very accurately, the observed relation between the half-period and the maximum energy of the disintegration particle¹. Though there seems to be a quantitative disagreement between Fermi's theory (applied to positrons) and positron disintegration, on the other hand the calculated values for K and Rb support Fermi's assumption of the existence of quadripole transitions of heavy particles, giving too big values for the half periods in comparison with the usual dipole disintegrations. The exceptional position of K and Rb is in some way rather *anschaulich*. We may remark that the Sargent-Fermi rule, in contrast to the Geiger-Nuttall law, shows a less pronounced dependence on the charge number, so that for qualitative considerations even the wave functions of free particles can be used. [中文](#)

The *second* order effects give specially the probability of production of pairs, which is in the case of the ψ -field less effective than in the electromagnetic case, as the charge, e , is much bigger than Fermi's coefficient, g (the "charge" for the ψ -field). The most important second order effect is the subsequent production and annihilation of an electron and positron, in the field of proton and neutron, which leads to the appearance of an interaction *exchange* energy (Heisenberg's *Austausch*) between proton and neutron, quite in the same way as Coulomb interaction can be conceived as arising from the birth and absorption of a photon in the case of two electrons. Instead of e^2/r one gets here an interaction of the order $g^2/\hbar r^5$, which is easily verified dimensionally. The exact calculations were first carried out by Prof. Ig. Tamm, who also insisted on development of this method. With $g \sim 10^{-50}$ (the computations were carried out by V. Mamasichlisov), which value is required by the empirical data on heavy radioactive bodies, we get an interaction energy of a million

volts, not at a distance of 10^{-13} cm. but only at $r \sim 10^{-15}$ cm., which is inadmissible. We may ask about the value of r , which would give a *self-interaction* energy of the order of the proper energy of a heavy particle. This value is of the order 10^{-16} cm., which is that of the classical radius of a proton. [中文](#)

The appearance of these small distances is very surprising and can be removed only by some quite new assumptions. Fermi's characteristic coefficient g appears to be connected also with distances of this order of magnitude. [中文](#)

(133, 981-982; 1934)

D. Iwanenko: Physical-Technical Institute, Leningrad.

Reference:

1. cf. D. Iwanenko, *C.R. Ac. Sci. U.S.S.R.*, Leningrad, **2**, No. 9, 1934.

中子和质子的相互作用

伊万年科

俄国物理学家德米特里·伊万年科在这篇文章中指出费米新近关于 β 辐射的理论尽管在某些方面获得了成功，但它也给出了一些错误的预测。对于在轻原子核中观察到的衰变现象，虽然该理论给出的衰变速率和放出的粒子的最大能量之间的关系是大致正确的，但是，如果使用该理论时考虑束缚核的相互作用，从而认为其是类似于电磁相互作用的作用——媒介粒子的交换，人们会发现这种作用力只有在核子之间的距离大约为 10^{-17} 米时才足够强，而这个距离太短了。因此，伊万年科得出结论认为费米的理论只是一个非常粗略的近似理论。 [英文](#)

由于电子和正电子都会在一些核反应中被原子核排斥出来，所以我们可以试着像处理原子所放射的光子一样处理这些轻粒子。于是，我们可以认为重粒子（质子、中子）之间的相互作用是通过 ψ 场方程所描述的轻粒子来实现的。这种相互作用与以电磁场或光子为介质的电磁相互作用（如库仑相互作用）具有相同的形式。 [英文](#)

一阶效应是电子的释放（或吸收），费米最近研究过这个问题，当然正电子的情况类似。我们注意到，将费米理论应用到产生正电子的轻核衰变时（我们是通过改变电荷数的符号并且赋予后者适当的数值来实现这一过程的），得到的理论结果与实验观察到的衰变粒子的半衰期和其最大能量之间的关系^[1]相符合，但不是精确吻合。虽然正电子的衰变和费米理论（应用于正电子）计算的结果似乎在数值上吻合得不是很好，但是从另一方面来看，K和Rb的计算结果却支持费米关于存在重粒子四极裂变的假设，由其计算给出的四极裂变的半衰期要远大于通常的偶极裂变的半衰期。K和Rb的特殊地位从某种程度上说可谓非常直观。

我们注意到对照盖革-努塔耳定律，萨金特-费米规则反而很少依赖于电荷数，因此在做定性分析时，甚至可以用自由粒子的波函数。 [英文](#)

二阶效应特别给出了产生粒子对的可能性。由于电荷 e 要远远大于费米系数 g （对应 ψ 场的“电荷”），所以相对于在电磁场中，在 ψ 场中产生粒子对的可能性要小。最重要的二阶效应是：在质子和中子场中，电子和正电子的产生和湮灭，导致了中子和质子之间相互作用的交换能（海森堡交换）的出现。这正如库仑相互作用可以看作是由两个电子之间光子的产生和吸收所导致的。不同于库仑作用中的比值 e^2/r ，重粒子的交换能与 $g^2/\hbar r$ 成正比，这个值可以很容易地从数量级上进行验证。塔姆教授首先进行了准确计算，他仍在坚持发展这一方法。根据重放射性物质的经验数值的要求，取 $g \sim 10^{-50}$ （由麻马斯克索夫计算得出），我们得到相互作用能为一兆电子伏，而这是在距离 $r \sim 10^{-15}$ cm而不是距离 $r \sim 10^{-13}$ cm时得到的，但是这个距离是不合理的。我们可能会对距离 r 值产生疑问，距离 r 应该给出一个对于重粒子来说数量级合理的自作用能量。这个值在 10^{-16} cm量级，即质子的经典半径的量级。 [英文](#)

出现这么小的间距实在是让人吃惊，只有引入某种新的假设才能解决这个问题。费米特征系数 g 也与这个间距的数量级大小有关。 [英文](#)

（王静 翻译；王乃彦 审稿）

A “Nuclear Photo-effect”: Disintegration of the Diplon by γ -rays

J. Chadwick and M. Goldhaber

In 1934, some physicists still doubted if the neutron were a genuine subatomic particle, or a composite of the proton and the electron. Here James Chadwick and Maurice Goldhaber describe their experimental determination of a significantly more accurate neutron mass. They used photons to induce the disintegration of a “diplon”—a nucleus of heavy hydrogen—into a proton and neutron. As the masses of the atoms of hydrogen and heavy hydrogen were known very accurately, it was then easy to deduce a value for the mass of the neutron. This experiment suggested that the diplon is composed of a neutron and proton, and helped cement the status of the neutron as a fundamental particle. [中文](#)

BY analogy with the excitation and ionisation of atoms by light, one might expect that any complex nucleus should be excited or “ionised”, that is, disintegrated, by γ -rays of suitable energy. Disintegration would be much easier to detect than excitation. The necessary condition to make disintegration possible is that the energy of the γ -ray must be greater than the binding energy of the emitted particle. The γ -rays of thorium C'' of $h\nu = 2.62 \times 10^6$ electron volts are the most energetic which are available in sufficient intensity, and

therefore one might expect to produce disintegration with emission of a heavy particle, such as a neutron, proton, etc., only of those nuclei which have a small or negative mass defect; for example, D^2 , Be^9 , and the radioactive nuclei which emit α -particles. The emission of a positive or negative electron from a nucleus under the influence of γ -rays would be difficult to detect unless the resulting nucleus were radioactive. [中文](#)

Heavy hydrogen was chosen as the element first to be examined, because the dipton has a small mass defect and also because it is the simplest of all nuclear systems and its properties are as important in nuclear theory as the hydrogen atom is in atomic theory. The disintegration to be expected is



Since the momentum of the quantum is small and the masses of the proton and neutron are nearly the same, the available energy, $h\nu - W$, where W is the binding energy of the particles, will be divided nearly equally between the proton and the neutron. [中文](#)

The experiments were as follows. An ionisation chamber was filled with heavy hydrogen of about 95 percent purity, kindly lent by Dr. Oliphant. The chamber was connected to a linear amplifier and oscillograph in the usual way. When the heavy hydrogen was exposed to the γ -radiation from a source of radiothorium, a number of "kicks" was recorded by the oscillograph. Tests showed that these kicks must be attributed to protons resulting from the splitting of the dipton. When a radium source of equal γ -ray intensity was employed, very few kicks were observed. From this fact we deduce that the disintegration cannot be produced to any marked degree by γ -rays of energy less than 1.8×10^6 electron volts, for there is a strong line of this energy in the radium C spectrum. [中文](#)

If the nuclear process assumed in (1) is correct, a very reliable

estimate of the mass of the neutron can be obtained, for the masses of the atoms of hydrogen and heavy hydrogen are known accurately. They are 1.0078 and 2.0136^1 respectively. Since the diplon is stable and can be disintegrated by a γ -ray of energy 2.62×10^6 electron volts (the strong γ -ray of thorium C"), the mass of the neutron must lie between 1.0058 and 1.0086; if the γ -ray of radium C of 1.8×10^6 electron volts is ineffective, the mass of the neutron must be greater than 1.0077. If the energy of the protons liberated in the disintegration (1) were measured, the mass of the neutron could be fixed very closely. A rough estimate of the energy of the protons was deduced from measurements of the size of the oscillograph kicks in the above experiments. The value obtained was about 250,000 volts. This leads to a binding energy for the diplon of 2.1×10^6 electron volts, and gives a value of 1.0081 for the neutron mass. This estimate of the proton energy is, however, very rough, and for the present we may take for the mass of the neutron the value 1.0080, with extreme errors of ± 0.0005 . 中文

Previous estimates of the mass of the neutron have been made from considerations of the energy changes in certain nuclear reactions, and values of 1.007 and 1.010 have been derived in this way^{2,3}. These estimates, however, depend not only on assumptions concerning the nuclear processes, but also on certain mass-spectrograph measurements, some of which may be in error by about 0.001 mass units. It is of great importance to fix accurately the mass of the neutron and it is hoped to accomplish this by the new method given here. 中文

Experiments are in preparation to observe the disintegration of the diplon in the expansion chamber. These experiments should confirm the nuclear process which has been assumed, and therewith the assumption that the diplon consists of a proton and a neutron. Both the energy of the protons and their angular distribution should also be

obtained. 中文

If, as our experiments suggest, the mass defect of the diplon is about 2×10^6 electron volts, it is at once evident why the diplon cannot be disintegrated by the impact of polonium α -particles⁴. When an α -particle collides with a nucleus of mass number M , only a fraction $M/(M + 4)$ of the kinetic energy of the α -particle is available for disintegration, if momentum is to be conserved. In the case of the diplon, therefore, only one third of the kinetic energy of the α -particle is available, and this, for the polonium α -particle, is rather less than 1.8×10^6 electron volts. The more energetic particles of radium C' should just be able to produce disintegration, and Dunning⁵ has in fact observed a small effect when heavy water was enclosed in a radon tube. 中文

Our experiments give a value of about 10^{-28} sq. cm. for the cross-section for disintegration of a diplon by a γ -ray of 2.62×10^6 electron volts. In a paper to be published shortly, H. Bethe and R. Peierls have calculated this cross-section, assuming the interaction forces between a proton and a neutron which are given by the considerations developed by Heisenberg, Majorana and Wigner. They have obtained the transition probability in the usual quantum-mechanical way, and their result gives a value for the cross-section of the same order as the experimental value, but rather greater, if we take the mass of the neutron as 1.0080. If, however, we take the experimental value for the cross-section, the calculations lead to a neutron mass of 1.0085, which seems rather high. Thus the agreement of theory with experiment may be called satisfactory but not complete. 中文

One further point may be mentioned. Some experiments of Lea⁶ have shown that paraffin wax bombarded by neutrons emits a hard γ -radiation greater in intensity and in quantum energy than when carbon alone is bombarded. The explanation suggested was that, in the collisions of neutrons and protons, the particles sometimes

combine to form a dipion, with the emission of a γ -ray. This process is the reverse of the one considered here. Now if we assume detailed balancing of all processes occurring in a thermodynamical equilibrium between dipions, protons, neutrons and radiation, we can calculate, without any special assumption about interaction forces, the relative probabilities of the reaction (1) and the reverse process. Using our experimental value for the cross-section for reaction (1), we can calculate the cross-section for the capture of neutrons by protons for the case when the neutrons have a kinetic energy $2(h\nu - W) = 1.0 \times 10^6$ electron volts in a co-ordinate system in which the proton is at rest before the collision. In this special case the cross-section σ_c for capture (into the ground state of the dipion—we neglect possible higher states) is much smaller than the cross-section σ_p for the “photo-effect”. It is unlikely that σ_c will be very much greater for the faster neutrons concerned in Lea’s experiments. It therefore seems very difficult to explain the observations of Lea as due to the capture of neutrons by protons, for this effect should be extremely small. A satisfactory explanation is not easy to find and further experiments seem desirable. 中文

(134, 237-238; 1934)

References:

1. K. T. Bainbridge, *Phys. Rev.*, **44**, 57; 1933.
2. J. Chadwick, *Proc. Roy. Soc., A*, **142**, 1; 1933.
3. I. Curie and F. Joliot, *Nature*, **133**, 721, May 12, 1934.
4. Rutherford and A. E. Kempton, *Proc. Roy. Soc., A*, **143**, 724; 1934.
5. *Phys. Rev.*, **45**, 586; 1934.
6. *Nature*, **133**, 24, Jan. 6, 1934.

一种“核的光效应”： γ 射线引发的氘核蜕变

查德威克，戈德哈伯

1934年，仍有一些物理学家对于中子是真正的亚原子粒子抑或是电子和质子的结合体而感到疑惑。这篇文章中，詹姆斯·查德威克和莫里斯·戈德哈伯描述了他们对于中子质量更为精确的实验测定。他们用光子引发“氘核”（重氢的原子核）蜕变为一个质子和一个中子。由于氢原子和重氢原子的质量已经有了非常精确的数值，所以据此可以很容易推算出中子的质量。这一实验表明氘核由一个中子和一个质子构成，该实验也更加牢固地确立了中子是一种基本粒子的理念。 [英文](#)

根据原子在光的照射下可以发生激发和电离，人们可以以此类推，任何具有复杂结构的原子核都会被具有适当能量的 γ 射线激发或者“电离”（即蜕变）。蜕变要比激发容易探测得多。蜕变发生的必要条件是 γ 射线的能量大于所放出的粒子的结合能。钷 C^{90} 放射出的 γ 射线的能量为 $h\nu = 2.62 \times 10^6$ 电子伏，这是能够得到的且具有足够强度的射线中能量最高的，因此，人们期望核蜕变可以产生某种重粒子（例如中子、质子等），而只有在蜕变中质量亏损较小或者为负值的原子核才能产生这种蜕变；像 2D 、 9Be 以及放射性原子核则放射出 α 粒子。由 γ 射线引起的正电子或负电子发射很难被探测到，除非形成的原子核具有放射性。 [英文](#)

首先选择重氢作为研究对象，因为氘核的质量亏损小，并具有最简单的核系统，而且氘核在核理论中的重要性就如同氢原子在原子理论中的一样。我们预期的蜕变反应是：

$${}^2\text{D} + h\nu \rightarrow {}^1\text{H} + {}^1_0\text{n}$$

(1)

由于光量子动量非常小，而且质子和中子的质量几乎相等，所以可获取的能量 $h\nu - W$ (W 是粒子的结合能) 几乎会在质子和中子间平分。

英文

实验过程如下：向电离腔中充满纯度为95%的重氢（重氢是奥利芬特博士慷慨赠予的），我们依照常规的方法将电离腔与一个线性放大器和示波器相连。当我们用放射性钷所放射的 γ 射线辐照重氢时，示波器就会记录到很多“突跳”。实验证明，这些突跳是氘核蜕变产生的质子引起的。如果我们用相同强度的镭源 γ 射线照射重氢，观察到的突跳就很少。由此我们推断，能量小于 1.8×10^6 电子伏的 γ 射线无法引发显著的蜕变，因为在镭C能谱的这个能量位置上有一条很强的线。

英文

如果式(1)中假设的核反应过程是正确的，因为氢原子和重氢原子的质量都是精确已知的，其值分别是1.0078和2.0136^[1]，所以我们可以对中子质量进行可靠的估算。由于氘核是稳定的，而且可以由能量为 2.62×10^6 电子伏的 γ 射线（钷C⁺放射的强 γ 射线）引发蜕变，所以中子质量一定在1.0058和1.0086之间；如果镭C发射的能量为 1.8×10^6 电子伏的 γ 射线不能引发蜕变，那么中子质量一定大于1.0077。如果蜕变反应式(1)中释放的质子能量是可以测量的，那么中子质量就能较为精确地确定了。通过测量上述实验中示波器上突跳的大小可以对质子的能量进行粗略估算，由此得到的能量数值约为250,000电子伏。由这个值导出氘核的结合能为 2.1×10^6 电子伏，中子质量为1.0081。不过，这种对质子能量的估算非常粗略，目前我们取中子质量为1.0080，最大误差为 ± 0.0005 。

英文

之前根据某些核反应的能量变化估算出来的^[2,3]中子质量值为1.007和1.010。然而，这些估算值不仅依赖于对于核过程的假设，还需依赖质谱测量，而有些质谱测量的误差会达到约0.001个质量单位。精确确定中子质量是十分重要的，我们希望这里给出的新方法能够成功解决这个问题。

英文

对膨胀云室中氘核蜕变进行观测的实验正在筹备之中。这些实验将会证实前面假设的核反应过程，进而证实氘核是由一个质子和一个中子

构成的。质子的能量以及它们的角分布也都将被测得。

[英文](#)

正如我们的实验所表明的那样，如果氘核的质量亏损约为 2×10^6 电子伏，那么氘核不能在钋放射出的 α 粒子的轰击下发生蜕变^[4]的原因就会立刻清楚了。当 α 粒子和一个质量数为 M 的原子核发生碰撞时，如果碰撞过程中动量是守恒的，那么在 α 粒子的动能中只有 $M/(M+4)$ 可以用于诱发蜕变。因此，在参与碰撞的原子核为氘核的情况中， α 粒子的动能只有 $1/3$ 可用于蜕变，而对于钋放射出的 α 粒子，这个能量小于 1.8×10^6 电子伏。而镭C'发射出的能量更高的粒子刚好可以引发蜕变，事实上，邓宁^[5]已经在将重水封装于氩管里的实验中观察到了微弱的蜕变效应。

[英文](#)

我们的实验给出了能量为 2.62×10^6 电子伏的 γ 射线所引发氘核蜕变时的碰撞截面为 10^{-28} 平方厘米。在近期即将发表的一篇论文中，贝特与佩尔斯假设中子和质子之间相互作用力符合海森堡、马约拉纳和维格纳提出的设想，从而计算出这个截面的数值。他们使用通常的量子力学方法计算了蜕变的概率，其理论计算给出的碰撞截面数值与实验值具有相同的数量级，但如果我们取中子质量为1.0080，计算值就会相当大了。然而，如果我们设碰撞截面为实验值，那么计算得到的中子质量就是1.0085，这个值似乎太大了。因此，我们只能说理论和实验基本相符，而并非完全一致。

[英文](#)

另外还有一点需要提及。利^[6]的一些实验表明，用中子轰击固体石蜡发射出一种硬 γ 射线，这种射线比单独轰击碳原子产生的射线的强度更强且量子能量更高。对此的解释是，中子和质子发生碰撞有时会结合成氘核，并释放出 γ 射线。这一过程是我们这里所研究的反应的逆过程。现在，如果我们假定氘核、中子、质子三者各自与射线之间的热力学平衡所涉及的所有过程都达到细致平衡，那么无需任何有关相互作用力的假定，我们就能计算出反应式(1)与其逆过程发生的相对概率。用我们在实验中测得的反应式(1)的截面数据，当中子具有 $2(h\nu - W) = 1.0 \times 10^6$ 电子伏的动能，且质子在碰撞前静止时，可以计算出质子俘获中子的俘获截面。在这种特殊情况下，俘获截面 σ_c （在这里我们只考虑俘获后氘核处于基态的情况，忽略了可能存在的更高的激发态）要比“光效应”截面 σ_p 小很多。对于利的实验中相关的快中子，俘获截面 σ_c

不可能非常大。因此，似乎很难将利在实验中的观测解释成为质子俘获了中子的结果，因为这个效应应该是非常微弱的。要想找到一个令人满意的解释并不是很容易，这似乎有待更进一步的实验。 [英文](#)

（王静 翻译；王乃彦 审稿）

Quantum Mechanics and Physical Reality

N. Bohr

In May 1935, Einstein, Podolsky and Rosen published a landmark paper arguing that quantum mechanics must be considered incomplete. They had described a thought experiment in which the values of some physical variables could be known before they were measured, implying that some aspect of physical reality must correspond to those variables, which quantum mechanics however failed to describe. Here Niels Bohr argues that their argument was flawed owing to an essential ambiguity in quantum mechanics, which demands that physical reality cannot be considered independently of the conditions that define an experiment. So began an argument over the completeness of quantum theory, and its apparent “non-local” character (the possibility of action at a distance), which continues to this day. [中文](#)

IN a recent article by A. Einstein, B. Podolsky and N. Rosen, which appeared in the *Physical Review* of May 15, and was reviewed in *Nature* of June 22, the question of the completeness of quantum mechanical description has been discussed on the basis of a “criterion of physical reality”, which the authors formulate as follows: “If, without in any way disturbing a system, we can predict with certainty the value of a physical quantity, then there exists an element of

physical reality corresponding to this physical quantity”. 中文

Since, as the authors show, it is always possible in quantum theory, just as in classical theory, to predict the value of any variable involved in the description of a mechanical system from measurements performed on other systems, which have only temporarily been in interaction with the system under investigation; and since in contrast to classical mechanics it is never possible in quantum mechanics to assign definite values to both of two conjugate variables, the authors conclude from their criterion that quantum mechanical description of physical reality is incomplete. 中文

I should like to point out, however, that the named criterion contains an essential ambiguity when it is applied to problems of quantum mechanics. It is true that in the measurements under consideration any direct mechanical interaction of the system and the measuring agencies is excluded, but a closer examination reveals that the procedure of measurements has an essential influence on the conditions on which the very definition of the physical quantities in question rests. Since these conditions must be considered as an inherent element of any phenomenon to which the term “physical reality” can be unambiguously applied, the conclusion of the above-mentioned authors would not appear to be justified. A fuller development of this argument will be given in an article to be published shortly in the *Physical Review*. 中文

(136, 65; 1935)

N. Bohr: Institute of Theoretical Physics, Copenhagen, June 29.

量子力学和物理实在

玻尔

1935年5月，爱因斯坦、波多尔斯基和罗森一起发表了一篇具有里程碑意义的论文，他们认为量子力学应该是不完备的。他们描述了这样一个理想实验，其中有些物理变量的值在测量前就是已知的，这意味着这些物理量对应于某些物理实在，但量子力学无法描述这些物理量。本文中尼尔斯·玻尔认为他们的理论有缺陷，因为在量子力学中有一个重要的地方未阐述清楚，即需要说清楚的是，不可能独立于实验所处的环境来考虑物理实在。由此引发了关于量子理论完备性和量子理论明显“非局域”特征（超距作用的可能性）的讨论，直到今天，这方面的讨论仍在继续。 [英文](#)

最近，爱因斯坦、波多尔斯基和罗森在5月15日的《物理学评论》上发表了一篇文章，6月22日的《自然》杂志对该文章进行了评论。基于“物理实在的判据”，他们在文章中讨论了量子力学描述的完备性问题并对该问题作了如下阐述：“假如系统没有受到任何形式的干扰，我们可以确切地预言物理量的值，并且认为存在某个物理实在的要素与该物理量相对应。” [英文](#)

正如以上作者所述，像经典理论那样，在量子理论中通过对与所研究的系统有短暂相互作用的其他系统进行测量，可以预言与描述该力学系统有关的任何一个变量；但与经典力学不同的是，在量子力学中永远不可能同时给出两个共轭变量的确定值，上述文章的作者们根据其判据认为，物理实在的量子力学描述是不完备的。 [英文](#)

然而，我想要指出的是，当把所谓的判据应用于量子力学的问题时将会出现基本定义模糊不清的问题。确实，前面已经假设在测量过程中不考虑系统与测量仪器之间任何直接的力学相互作用，但是进一步的研

究表明，测量过程对现在我们所讨论的物理实在的确切定义有重要的影响。只有考虑测量过程对系统的影响并把这些影响看成是任何一个物理现象的内在属性，我们才可以明确地使用“物理实在”这个术语，因此，以上提到的那些作者们的结论似乎就不太合理了。不久，进一步完整地论证这个问题的文章将发表在《物理学评论》上。 [英文](#)

（沈乃澂 翻译；李军刚 审稿）

Isotopic Constitution of Uranium

A. J. Dempster

Uranium has the highest atomic weight of any naturally occurring element, and exists predominantly in the form of uranium-238. Here, however, physicist Arthur Dempster of the University of Chicago reports that about 0.4% of the element is an unstable isotope uranium-235. This isotope, he suggests, is the origin of the actinium series of radioactive elements, as the elements protactinium-231, actinium-227, francium-223 and so on can be generated by radioactive alpha and beta decays. Dempster also notes that another isotope, uranium-234, appears to exist in traces of 0.008%. Uranium-235 would soon become very important as the only natural fissile isotope: one capable of sustaining a nuclear chain reaction driven by slow moving neutrons, thus making nuclear power and atomic bombs conceivable. [中文](#)

THE analysis of uranium rays from the volatile hexafluoride by Dr. Aston¹ has shown a single line at atomic weight 238. The element appeared to be simple to at least two or three percent, but its properties were not favourable for study in the gas discharge. As uranium is of great importance for the subject of radioactivity, the spark source described in *Nature* of April 6 (135, 542) was tried with uranium metal and gold as electrodes, and also with an electrode made by packing a nickel tube with pitchblende. It was found that an exposure of a few seconds was sufficient for the main component at

238 reported by Dr. Aston; but in addition on long exposures a faint companion of atomic weight 235 was also present. With two different uranium electrodes it was observed on eight photographs, and two photographs with the pitchblende electrode also showed the new component. The relative intensity could be only roughly estimated on account of the irregularity of the spark, but it appeared to be less than one percent of the intensity of the main component. 中文

This faint isotope of uranium is of special interest as it is in all probability the parent of the actinium series of radioactive elements. In discussing Dr. Aston's analysis² of the isotopes in lead from radioactive minerals, Lord Rutherford³ pointed out that the lead isotope of atomic weight 207 is probably the end product of the actinium series, so that the atomic weight of protoactinium would be 231, $(207 + 6 \times 4)$. This value has been verified by the recent chemical determination of the atomic weight by v. Grosse⁴. Protoactinium itself may be formed by α - and β -ray transformations from a hypothetical isotope of uranium, actino-uranium, with an atomic weight of 235 or 239³. The relative amount of actino-uranium at present on the earth would be 0.4 percent of the uranium according to a recalculation by Dr. v. Grosse^{5,6}. The present observations thus support this theory, with the atomic weight of 235 for the isotope actino-uranium. A third isotope, uranium II, of atomic weight 234 amounts theoretically to only 0.008 percent of the uranium, and would be too faint for observation by the mass-spectrograph. 中文

(136, 180; 1935)

A. J. Dempster: University of Chicago, July 12.

References:

1. Aston, *Nature*, **128**, 725; 1931.
2. Aston, *Nature*, **123**, 313; 1929.
3. Rutherford, *Nature*, **123**, 313; 1929.
4. A. v. Grosse, *Proc. Roy. Soc.*, **150**, 363; 1935.

5. A. v. Grosse, *Phys. Rev.*, **42**, 565; 1932.
6. A. v. Grosse, *J. Phys. Chem.*, **38**, 487; 1933.

铀的同位素构成

登普斯特

自然界中存在的元素中，铀具有最大的原子量，且绝大部分以铀-238的形式存在。而在这篇文章中芝加哥大学的物理学家阿瑟·登普斯特指出，约有0.4%的铀是不稳定的同位素铀-235。他认为这种铀的同位素是铀系放射性元素的起源，因为镤-231、钍-227、镭-223等铀系放射性元素可通过该同位素的 α 衰变和 β 衰变而获得。同时登普斯特还注意到了铀的另一个同位素——铀-234，它只占0.008%。作为仅有的天然可裂变的同位素，铀-235很快变得非常重要：它可以维持一个由慢中子驱动的链式核反应，这使得核能和原子弹成为可能。 [英文](#)

阿斯顿博士^[1]对挥发性六氟化铀中的铀离子束的分析显示出一条对应于原子量为238的单线。至少在2%或3%的精度上讲这种元素的同位素构成是简单的，但是它的性质却很不适于利用气体电离的方法进行研究。鉴于铀对于放射性研究的巨大重要性，我们使用了4月6日发表于《自然》第135卷第542页的论文中所描述的火花源的方法，我们以金属铀和金作为电极，还使用了填充沥青铀矿的镍管为电极。实验发现，对于阿斯顿博士所报道的原子量为238的主要成分来说，几秒钟的曝光时间就已足够；但是除此之外，在长时间曝光后，一个原子量为235的微弱伴线也出现了。采用两个不同的铀电极，我们在八张照片中观察到了这条伴线，同时在两张使用沥青铀矿电极的照片中也显示了这一新成分的存在。由于火花的不均匀性，对新成分的相对强度只能进行粗略地估算，不过它的强度似乎不到主要成分的1%。 [英文](#)

铀的这种少量的同位素引起了我们特别的关注，因为它很可能是铀系放射性元素的母体。在就阿斯顿博士对放射性矿物中铅同位素的分析

结果^[2]进行讨论时，卢瑟福勋爵^[3]指出，原子量为207的铅同位素可能是铀系元素的最终产物，因此镤元素的原子量应为231，即

$(207 + 6 \times 4)$ 。冯·格罗塞^[4]采用新近的原子量化学测定法对这个值进行了确认。镤本身可以由一种假定的铀同位素（铀，原子量为235或239）通过 α 衰变或 β 衰变而形成^[3]。根据冯·格罗塞博士的重新计算^[5,6]，目前地球上的铀的相对含量大约为铀的0.4%。因此，就原子量为235的同位素铀而言，目前的观测结果是支持该理论的。第三种同位素——原子量为234的铀II，理论上只占铀总量的0.008%，这个量对于质谱观测来说可能过少了。 [英文](#)

（王耀杨 翻译；汪长征 审稿）

The Fundamental Paradox of the Quantum Theory

R. Peierls

Rudolph Peierls here writes to counter a recent argument of George Temple, who had apparently demonstrated an inconsistency in quantum mechanics. Temple had assumed that one unique quantum-mechanical operator (a mathematical construct of the theory) must correspond to each of the classical variables of motion, such as positions and momenta. Peierls questions this assumption, noting that the order in which variables appear in the mathematical formalism matters in quantum theory, while it does not in classical theory. In this property of so-called non-commutation, in fact, lies the origin of Heisenberg's uncertainty principle. 中文

THE question of the logical consistency of quantum mechanics has recently been discussed by Prof. G. Temple¹ and by Dr. H. Fröhlich and Dr. E. Guth². Temple arrives at an apparent contradiction, starting from principles which he states to be an essential part of quantum theory. From these principles contradictory results follow, as Temple shows by a perfectly rigorous deduction. (The existence of this deduction seems to have been ignored by Fröhlich and Guth.) 中文

The main assumption used by Temple is that to every function of the

classical variables of motion (momentum, co-ordinate, etc.) there corresponds one unambiguously defined operator which may be taken as the representative of this function in quantum mechanics. Although this assumption can be found quite frequently in papers discussing the principles of quantum theory, and even in some text-books, I would like to emphasise that it is not at all necessary and—as one can see from Temple's argument—not even possible in quantum mechanics.

中文

Quantum mechanics requires operators as representatives of physical variables for two purposes: to connect wave functions with experiments, actual or possible, and to calculate the time dependence of the wave function. In order to be able to apply quantum mechanics unambiguously to actual problems, one must, therefore, know (a) the operator representing the quantity measured by any given apparatus, and (b) the energy operator for any given physical system. Properly speaking, (a) is a special case of (b), for the properties of a measuring apparatus can always be analysed if its interaction energy with the object in question is known. 中文

If, then, we had an apparatus built in such a way as to measure, say, qp^2q (p denoting the momentum, q the co-ordinate of a particle), this apparatus would be *different* from an apparatus measuring $\frac{1}{2}(p^2q^2 + q^2p^2)$, although in the limiting case of classical mechanics, where quantum effects are negligible, both would measure the same quantity. 中文

Before applying such an apparatus (assuming, for the sake of argument, that it exists although it probably does not) one would have to make sure, either by experimental investigation or by applying quantum mechanics to its working mechanism, which operator actually is to be associated with it. In other words, an apparatus which is quite suitable for measuring a certain quantity in the classical limit may not satisfy our requirements if we rebuild it on a smaller scale, because then quantum effects will have to be taken into consideration.

That one never meets with any difficulty about the order of factors in the usual applications of quantum theory is due to the fact that only very simple operators occur in practice. The most typical of them is the energy of an electron in a field of force, $p^2/2m + V(q)$ (m = mass, V = potential energy). One generally assumes that the function in this exact form, without quantum corrections, has to be taken as the energy operator of a particle the energy of which would be given by the same expression in classical mechanics. This assumption seems very *natural*, but it cannot be *proved* on mere theoretical grounds. All one can say is that this expression is the *most plausible* amongst a variety of different expressions, which all become equal in the classical limit but differ by terms like, for example, $pV - Vp = (h/2\pi i) \text{grad } V$ (h = Planck's constant). It is for the experiment to show that the most plausible choice corresponds to reality and that such correction terms are absent. 中文

That the absence of these correction terms cannot be inferred from mere theoretical considerations is proved by the fact that when relativity and spin corrections are taken into account, such terms actually *do occur*. 中文

(136, 395; 1935)

R. Peierls: Physical Laboratory, University, Manchester, Aug. 5.

References:

1. *Nature*, **135**, 957, June 8, 1935.
2. *Nature*, **136**, 179, Aug. 3, 1935.

量子理论的基本佯谬

佩尔斯

鲁道夫·佩尔斯在本文中反驳了乔治·坦普尔最近的一个观点，当时坦普尔显然已经证明了量子力学中存在一个矛盾。坦普尔认为应该有唯一的量子力学算符（量子理论的数学表示）对应于每个经典的运动变量，如位置和动量。佩尔斯对坦普尔的这个结论表示质疑，他指出在量子理论中变量在数学表达式里的次序是很重要的，而在经典理论中是无关紧要的。事实上，海森堡测不准原理就是源于这种所谓的算符的不对易性。 [英文](#)

最近，坦普尔教授^[1]、弗勒利希博士和古思博士^[2]都讨论了量子力学的逻辑一致性问题。坦普尔从他所陈述的量子理论的基本原理出发得出了一个明显的矛盾。这些矛盾的结果正是坦普尔从量子力学的基本原理出发通过严密精确的推导得到的。（弗勒利希博士和古思博士似乎并没有注意到坦普尔已做的相关推导。） [英文](#)

坦普尔的主要假设是：经典运动变量（如动量、坐标等）的每一个函数都有一个明确定义的算符与之相对应，这些算符可以被视为相应的函数在量子力学中的表示形式。虽然我们可以经常在讨论量子理论基本原理的文章中，甚至是相关的教科书中看到这个假设，但是，我想强调的是，从坦普尔的论证过程中可以看到，在量子力学中，这个假设并不必要，甚至是不合理的。 [英文](#)

量子力学需要算符作为物理变量的表示形式有两个目的：一是将波函数与已经实现或可能实现的实验联系起来；二是计算波函数随时间的变化关系。为了能将量子力学明确地应用到实际的问题中，我们必须知道：（a）任意给定装置所测量的量的对应算符，（b）任意给定的物理系统对应的能量算符。严格地说，（a）是（b）的特殊情况，因为如果

测量装置与所考虑物体的相互作用能是已知的话，我们总可以对测量装置的性质进行分析。 [英文](#)

譬如说，我们有这样一台用来测量 qp^2q （ p 表示粒子的动量， q 表示粒子的坐标）这个量的测量装置，另外一台测量装置是用于测量 $\frac{1}{2}(p^2q^2 + q^2p^2)$ 的，虽然在经典力学的极限情况下，量子效应可以忽略不计，测量以上两个量的结果是一样的，但是以上两个测量装置本质上却是不一样的。 [英文](#)

在应用这类测量装置之前（为了论证方便，虽然这个测量装置可能并不存在，但我们仍假定它存在）我们必须确定，不管是在实验研究中还是在应用量子力学的工作机制中，哪个算符与它们相联系。换句话说，一个在经典极限情况下适于测量某个量的装置，如果改装并放到小尺度空间中进行测量，则可能不符合测量要求，因为这时候我们需要考虑量子效应了。 [英文](#)

我们在量子理论的日常应用中，并没在表达式中因子的次序上遇到问题，这是因为通常在实际情况中只会出现一些非常简单的算符。这些简单算符中最典型的是处在力场中电子的能量算符， $p^2/2m + V(q)$ （ m 表示电子的质量， V 表示势能）。我们通常认为，不考虑量子修正的话，这个严格表达式中的函数是粒子的能量算符，并且该能量算符给出的系统能量与经典力学中的表达式是一致的。这个假设似乎顺理成章，但是单凭理论推导并不能证明这个假设是对的。我们只能说这个表达式是众多不同的表达形式中看似最合理的一个，而这些不同的表达形式一般在经典极限下是等价的，除非有如 $pV - Vp = (h/2\pi i) \Delta V$ （ h 表示普朗克常数）的项存在时，它们才不一样。实验表明，关于表达式最合理的选择应与现实情况相对应，这时这些修正项便消失了。 [英文](#)

实际上，当我们考虑相对论和自旋修正的时候，这些量子效应的修正项的确出现了，这表明我们不能单纯地从理论推导的角度得出这些修正项不存在的结论。 [英文](#)

（沈乃澍 翻译；李军刚 审稿）

Uncertainty Principle and the Zero-point Energy of the Harmonic Oscillator

R. A. Newing

In 1913, Albert Einstein and Otto Stern suggested that measurements of the specific heat of hydrogen gas (a measure of how heat input changes its temperature) at low temperature could best be understood if the energy of the molecular vibrations could never be strictly zero, but had an irreducible residual energy. Theorists subsequently predicted such a residual, later known as the zero-point energy, from the equations of quantum mechanics. But the effect lacked intuitive justification. Here R. A. Newing shows that the zero-point energy can be seen as a consequence of Heisenberg's uncertainty principle, which forbids complete specification of position or momentum. Newing shows that the minimal possible value for the zero-point energy is consistent with that derived previously from quantum theory. [中文](#)

ACCORDING to quantum mechanics, an oscillator possesses a definite zero-point energy of vibration, and an attempt has been made to express this result *directly* in terms of some general principle. It has been found that the result may be deduced from the uncertainty principle, in view of the particular relation between position,

momentum and energy in a simple harmonic field.

[中文](#)

In a state of zero energy the vibrating particle would be at rest at the centre of the field, and its position and momentum would both be known accurately. But this would contradict the uncertainty principle, and the state is therefore not possible. The value of the minimum energy may be calculated from the uncertainty relation $\Delta p \Delta q \geq h/2\pi$. The linear harmonic oscillator is defined by the energy equation

$$W = \frac{1}{2} \mu \omega^2 q^2 + \frac{1}{2} p^2 / \mu = \text{constant}.$$

If we interpret

amplitude of $q = \Delta q =$ uncertainty in position,

amplitude of $p = \Delta p =$ uncertainty in momentum,

then

$$W = \frac{1}{2} \mu \omega^2 (\Delta q)^2 = \frac{1}{2} (\Delta p)^2 / \mu,$$

giving

$$\mu \omega \Delta q = \pm \Delta p.$$

For real Δp the positive sign must be taken, and from the uncertainty relation, $(\Delta p)^2 \geq h \mu \omega / 2\pi$, and therefore $W \geq \frac{1}{2} h \omega / 2\pi$. Taking the equality sign for the least value of the energy, it follows that the zero-point energy is $\frac{1}{2} h \omega / 2\pi$. [中文](#)

(136, 395; 1935)

测不准原理和谐振子的零点能

纽因

1913年，阿尔伯特·爱因斯坦和奥托·斯特恩提出，如果在任何情况下，分子振动能量都不会完全等于零，而是存在着一个无法消除的残余能量，那么低温下氢气比热的测量（一项关于氢气温度随输入热量变化的测量）结果就能得到很好的解释了。紧接着，理论物理学家们从量子力学的方程中推导出了这一残余能量，其后来被称之为零点能。但是这一效应缺乏直观的合理性。这篇文章中，纽因认为零点能可以被看作是海森堡的测不准原理的推论，测不准原理认为不能同时精确的获知微观粒子的位置和动量。纽因的结果表明零点能的可能最小值与之前根据量子理论推导出的结果是一致的。

英文

根据量子力学原理，一个振子具有确定的振动零点能，科学工作者也正在试图使用一些基本的原理来对这一结果进行直接的表述。在简单的谐波场中，考虑到位置、动量和能量之间的特殊关系，我们发现或许可以根据测不准原理推导出零点能。

英文

处于零点能态的振动粒子如果会静止于场的中央，那么它的位置和动量都能准确地确定下来。但是这与测不准原理相矛盾，因此谐振子是不可能处于这种态的。我们可以根据测不准关系 $\Delta p \Delta q \geq h/2\pi$ 计算出能量的最小值。一维谐振子的能量是由下面的能量方程定义的

$$W = \frac{1}{2} \mu \omega^2 q^2 + \frac{1}{2} p^2 / \mu = \text{常数}$$

如果我们这样理解：

$$q \text{ 的大小} = \Delta q = \text{位置不确定度}$$

p 的大小 = Δp = 动量不确定度

于是有

$$W = \frac{1}{2} \mu \omega^2 (\Delta q)^2 = \frac{1}{2} (\Delta p)^2 / \mu$$

得出

$$\mu \omega \Delta q = \pm \Delta p$$

对于实数 Δp ，必须取正号，根据测不准关系，我们推导出

$(\Delta p)^2 \geq h \mu \omega / 2\pi$ ，因此可得， $W \geq \frac{1}{2} h \omega / 2\pi$ 。当求能量的最小值时取等号，于是得到零点能为 $\frac{1}{2} h \omega / 2\pi$ 。

英文

（沈乃澍 翻译；李淼 审稿）

The Slowing Down of Neutrons by Collisions with Protons

H. von Halban, Jr. and P. Preiswerk

Fermi had recently shown that neutrons passing through substances containing hydrogen would be slowed by collisions with protons. Here Hans von Halban and Peter Preiswerk explore the process in detail. They note that neutrons of relatively low energy might well be slowed as they transfer energy to the molecules of the medium, in which case the slowing might be influenced by the molecular nature of the medium. So they passed neutrons through water, ethyl alcohol, benzene and liquid paraffin, measuring how the intensity of slow neutrons depended on distance travelled. The results showed that indeed the degree of slowing seemed likely to reflect differences in molecular motions. Slowing of neutrons was later to prove essential for controlled nuclear fission. [中文](#)

FERMI and others¹ showed that neutrons, passing through substances containing hydrogen, lose their energy by collisions with protons. It is of interest to discuss this process of slowing down somewhat further. So long as the energy of the neutron is higher than the energy with which the protons are bound in the molecules of the substance through which the neutrons pass, it seems evident that the latter give, on the average, half their energy to the proton at every collision. But when the neutrons are slowed down below this binding energy, they

must excite rotation and oscillation of the hydrogen atom in the molecule in order to lose energy. [中文](#)

It is not certain whether the cross-section of protons for neutrons is a uniform function of the velocity of the neutrons, or if it shows discontinuities for energies comparable with the molecular bindings. In the latter case, it is possible that two substances, containing hydrogen held by different linkages, would show differences in slowing down the neutrons. We have carried out some experiments which indicate the existence of such differences. [中文](#)

Spheres with different radii (5–15cm.) were alternately filled with water (0.11 gm. H/cm.³), ethyl alcohol (0.10 gm. H/cm.³), benzene (0.067 gm. H/cm.³) and a liquid paraffin (0.14 gm. H/cm.³). In the centre of the sphere a neutron source (radon + beryllium) was placed. The activation of a silver plate, which was fixed on the surface of the spheres and exposed for five minutes to irradiation, served as a measure of the intensity of slow neutrons. [中文](#)

Fig. 1 shows the number of slow neutrons per unit of the solid angle plotted against rd , where r is the radius of the sphere and d the quantity of hydrogen contained by 1 cm.³ of the liquid in question. The general aspect of these curves is already known. For small radii a rapid increase of the intensity with increasing radius is observed, due to the slowing down of neutrons by collisions with protons. After a certain point, an increase of the radius causes a reduction of the intensity. This clearly shows that not all neutrons which pass the surface of a sphere are reaching the next bigger sphere. The vanishing of slow neutrons must be ascribed to absorption. [中文](#)

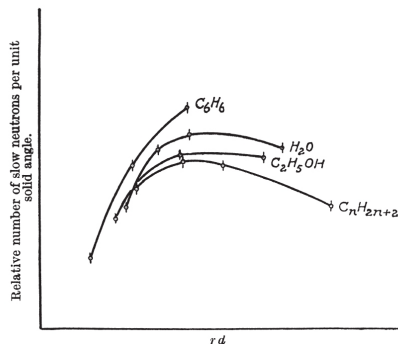


Fig. 1 中文

The absorption of slow neutrons by paraffin and other substances containing hydrogen has been studied in detail by Bjerger and Westcott², who found that the number of slow neutrons is reduced to a half after diffusion through 1.6 cm. of water. By a different method we obtained the value of 2.5 cm. for paraffin in a preliminary experiment. A source of neutrons was placed in the centre of a paraffin wax cube of 14 cm. side. Five plates of paraffin wax, each 1 cm. thick, and finally a small silver plate were placed upon this cube. A screen of cadmium was interposed between the paraffin plates at different distances from the silver plate. The activity of the silver, obtained for equal times of irradiation, increased when the distance between the silver and the cadmium was increased. A curve was obtained which showed that influence of the absorption of the cadmium decreased to a half when the distance between the silver plate and the absorber was increased by 2.5 cm. 中文

Fig. 1 shows that the maximum values of intensity are different for different liquids; these differences cannot be ascribed to the quantities of hydrogen contained by the liquids alone. Also, it is not possible to explain these results by absorption of slow neutrons by oxygen or carbon nuclei. A neutron has, for the same number of collisions with protons, passed twice the number of carbon atoms in benzene as in the liquid paraffin, and we see that the maximum value for the latter is much lower than for benzene, where the maximum seems to be just

reached with the biggest sphere. [中文](#)

The differences in the influence of the four liquids examined, on the intensity of slow neutrons, cannot be ascribed to differences in the quantities of hydrogen, carbon or oxygen these liquids contain. Other differences between these liquids depend upon their molecular structure. Thus different probabilities for the slowing down of neutrons by excitation of rotation and oscillation of the hydrogen atoms in the different molecules may account for the discrepancies observed. [中文](#)

(136, 951-952; 1935)

Hans von Halban, Jr. and Peter Preiswerk: Institut du Radium, Laboratoire Curie, Paris, Nov. 5.

References:

1. Fermi and others, *La Ricerca Scientifica*, (v) **2**, 1; 1934. (vi) **1**, 1; 1935.
2. T. Bjerge and C. H. Westcott, *Proc. Roy. Soc., A*, **150**, 709; 1935.

与质子碰撞而导致的中子慢化

小哈尔班，普雷斯沃克

费米于近期指出中子穿过含氢物质时会与质子碰撞而减速。这篇文章中汉斯·冯·哈尔班和彼得·普雷斯沃克仔细探讨了这一过程。他们注意到能量相对较低的中子会由于将能量传递给介质分子而减速，在这种情况下，中子减速可能受到介质分子性质的影响。因此，他们使中子穿过水、酒精、苯和液体石蜡，以测量慢中子的强度是如何随穿透深度的变化而变化的。实验结果显示中子慢化的程度似乎反映出了介质分子运动的差别。后来，中子慢化被证明对于可控核裂变是非常关键的。 [英文](#)

费米等人^[1]指出，中子在通过含氢的物质时会因与质子发生碰撞而损失能量。进一步深入地讨论这一慢化过程是有趣的。只要中子的能量大于它要通过的物质分子中质子的束缚能，中子平均在每一次的碰撞过程中就会有一半能量传给了质子，这点似乎是很明显的。但当中子的能量减少到这种束缚能以下时，中子就一定会激发分子中氢原子的转动和振动，从而使中子的能量减少。 [英文](#)

不能确定的是：中子对质子的碰撞截面是否为中子速度的单调函数，或者当中子能量与分子的束缚能可比时，碰撞截面是否呈现不连续性。在后一种情况下，两种含有不同结合形式氢的物质在中子慢化的过程中可能会表现出差异性。我们已经进行了一些实验，结果显示出了这种差异性的存在。 [英文](#)

用水（氢含量为 0.11 g/cm^3 ）、乙醇（氢含量为 0.10 g/cm^3 ）、苯（氢含量为 0.067 g/cm^3 ）和液体石蜡（氢含量为 0.14 g/cm^3 ）分别装满半径不同（ $5 \sim 15 \text{ cm}$ ）的球。在球的中央放置着一个中子源（钋+铍），在球的表面安置一个银片并对其辐照5分钟，然后利用银片的

放射性测量慢中子的强度。

英文

图1显示了单位立体角中慢中子的数量随着 rd 的变化关系，其中 r 是球的半径， d 是 1cm^3 液体的含氢量。这些曲线的一般意义是众所周知的。对小半径而言，随着半径的增大，观测到中子的强度显著增加，这是由于中子与质子碰撞而速度减慢。在某一个固定值之后，随着半径的增大，中子的强度反而减弱。这清楚地表明，并不是所有通过球表面的中子都会到达下一个更大的球面上。慢中子的消失必然是因为它被吸收了。

英文

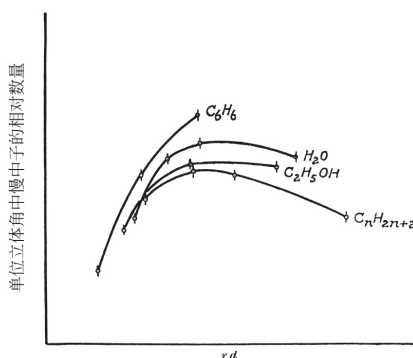


图1 英文

伯格和韦斯科特^[2]已经详细地研究了石蜡和其他含氢物质对慢中子的吸收，他们发现，其在通过厚1.6cm的水之后，慢中子的数量减少了一半。在对石蜡进行的初步实验中，我们采用不同的方法得到的数值为2.5cm。把一个中子源放在边长为14cm的立方体形石蜡的中心，在这个立方体石蜡上放置5个1cm厚的石蜡板，最后放置一块小银板。在石蜡板之间插入一块镉片，并变换其位置以使其与银板的距离不同。在相等辐射时间内，当银板和镉板的距离增大时，银的放射性会增加。由实验得到的曲线表明，当银板与镉板之间的距离增大了2.5cm时，镉吸收的影响减小到一半。

英文

图1表明，对不同的液体，慢中子强度的最大值是不相同的；这些差别不能仅仅归因于液体中氢含量的不同。同样，也不能用氧核或碳核吸收慢中子来解释。在与质子碰撞次数相同的情况下，中子在苯中通过的碳原子数是在液体石蜡中通过碳原子数的两倍，而且我们还发现，液体石蜡中慢中子强度的最大值远远低于在苯中慢中子强度的最大值，而

苯中的最大值似乎得用半径最大的球才刚能达到。

[英文](#)

被测试的四种液体对于慢中子强度的影响力的差别，不能仅归因于是这些液体中氢、碳或氧含量的不同。这些液体的分子结构的不同也导致了它们之间的其他一些差别。因此，或许我们可以这样解释观测到的差别，即不同分子中通过激发氢原子的转动和振动来减慢中子的概率不同。

[英文](#)

（沈乃澂 翻译；王乃彦 审稿）

Viscosity of Liquid Helium below the λ -point

P. Kapitza

Earlier experiments had noted strange behaviour in liquid helium at temperatures below about 2.18K, where the liquid conducts heat with extraordinary efficiency. Here, physicist Pyotr Kapitza suggests that a dramatic decrease in the fluid's viscosity might explain the phenomenon, as it would make heat transport by convection much easier. Some recent experiments, he notes, had measured a decrease in the viscosity, but now his group, in a much more sensitive experiment, has found that the viscosity of the liquid below 2.18K is at least 10,000 times smaller than that of any other known substance. Kapitza suggested this might be explained if liquid helium becomes a “superfluid” at low temperatures, perhaps even flowing with no viscosity at all. [中文](#)

THE abnormally high heat conductivity of helium II below the λ -point, as first observed by Keesom, suggested to me the possibility of an explanation in terms of convection currents. This explanation would require helium II to have an abnormally low viscosity; at present, the only viscosity measurements on liquid helium have been made in Toronto¹, and showed that there is a drop in viscosity below the λ -point by a factor of 3 compared with liquid helium at normal pressure, and by a factor of 8 compared with the value just above the λ -point. In these experiments, however, no check was made to ensure

that the motion was laminar, and not turbulent.

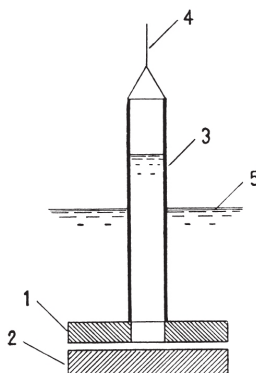
[中文](#)

The important fact that liquid helium has a specific density ρ of about 0.15, not very different from that of an ordinary fluid, while its viscosity μ is very small comparable to that of a gas, makes its kinematic viscosity $\nu = \mu/\rho$ extraordinary small. Consequently when the liquid is in motion in an ordinary viscosimeter, the Reynolds number may become very high, while in order to keep the motion laminar, especially in the method used in Toronto, namely, the damping of an oscillating cylinder, the Reynolds number must be kept very low. This requirement was not fulfilled in the Toronto experiments, and the deduced value of viscosity thus refers to turbulent motion, and consequently may be higher by any amount than the real value.

[中文](#)

The very small kinematic viscosity of liquid helium II thus makes it difficult to measure the viscosity. In an attempt to get laminar motion the following method (shown diagrammatically in the accompanying illustration) was devised. The viscosity was measured by the pressure drop when the liquid flows through the gap between the disks 1 and 2; these disks were of glass and were optically flat, the gap between them being adjustable by mica distance pieces. The upper disk, 1, was 3 cm. in diameter with a central hole of 1.5 cm. diameter, over which a glass tube (3) was fixed. Lowering and raising this plunger in the liquid helium by means of the thread (4), the level of the liquid column in the tube 3 could be set above or below the level (5) of the liquid in the surrounding Dewar flask. The amount of flow and the pressure were deduced from the difference of the two levels, which was measured by cathetometer.

[中文](#)



中文

The results of the measurements were rather striking. When there were no distance pieces between the disks, and the plates 1 and 2 were brought into contact (by observation of optical fringes, their separation was estimated to be about half a micron), the flow of liquid above the λ -point could be only just detected over several minutes, while below the λ -point the liquid helium flowed quite easily, and the level in the tube 3 settled down in a few seconds. From the measurements we can conclude that the viscosity of helium II is at least 1,500 times smaller than that of helium I at normal pressure.

中文

The experiments also showed that in the case of helium II, the pressure drop across the gap was proportional to the square of the velocity of flow, which means that the flow must have been turbulent. If, however, we calculate the viscosity, assuming the flow to have been laminar, we obtain a value of the order 10^{-9} C.G.S., which is evidently still only an upper limit to the true value. Using this estimate, the Reynolds number, even with such a small gap, comes out higher than 50,000, a value for which turbulence might indeed be expected.

中文

We are making experiments in the hope of still further reducing the upper limit to the viscosity of liquid helium II, but the present upper

limit (namely, 10^{-9} C.G.S.) is already very striking, since it is more than 10^4 times smaller than that of hydrogen gas (previously thought to be the fluid of least viscosity). The present limit is perhaps sufficient to suggest, by analogy with superconductors, that the helium below the λ -point enters a special state which might be called a “superfluid”. [中文](#)

As we have already mentioned, an abnormally low viscosity such as indicated by our experiments might indeed provide an explanation for the high thermal conductivity, and for the other anomalous properties observed by Allen, Peierls, and Uddin². It is evidently possible that the turbulent motion, inevitably set up in the technical manipulation required in working with the liquid helium II, might on account of the great fluidity, not die out, even in the small capillary tubes in which the thermal conductivity was measured; such turbulence would transport heat extremely efficiently by convection. [中文](#)

(141, 74; 1938)

P. Kapitza: Institute for Physical Problems, Academy of Sciences, Moscow, Dec.3.

References:

1. Burton, *Nature*, **135**, 265 (1935); Wilhelm, Misener and Clark, *Proc. Roy. Soc., A*, **151**, 342 (1935).
2. *Nature*, **140**, 62 (1937).

液态氦在 λ 点以下的黏度

卡皮查

在以往的实验中曾记录到一种奇怪的现象，当温度低于约2.18 K时，液氦的热导率惊人的高。在这篇文章中，物理学家彼得·卡皮查认为这一物理现象是由于液体黏度的急剧减小所造成的，因为这样会使得对流传热更加容易。他注意到最近一些实验测量到黏度的减小，但现在他的研究组通过更为精确的实验发现，低于2.18 K时液氦的黏度至多是其他已知物质的测量值的1/10,000。卡皮查认为如果液氦在这样的低温下变成了“超流体”，甚至流动时黏度为零，那么这个实验就能得到解释。 [英文](#)

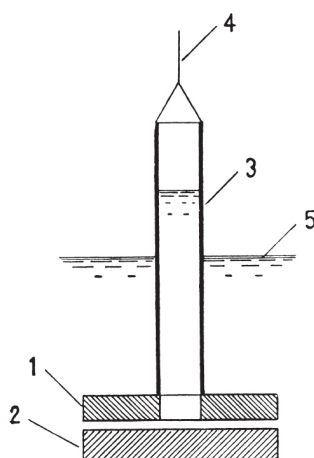
如同凯索姆首次观测到的那样，液氦II在 λ 点之下时表现出了异常高的热导率，这启发了我：也许可以用对流对它进行解释。如果这样解释的话就要求氦II的黏度非常小；到目前为止，仅有的对液氦黏度的测量是在多伦多进行的^[1]，测量结果显示，低于 λ 点时液氦的黏度是常压下的1/3，是略微高于 λ 点时的1/8。然而，在上述实验中，并没有完全确认液氦的运动形式就是层流，而不是湍流。 [英文](#)

重要的是，由于液氦的比重 ρ 大约为0.15，与普通流体没有很大差别，但其黏度 μ 与普通气体相比却非常小，这样就使得液氦的动力黏度 $\nu = \mu/\rho$ 格外的小。于是，当液氦在普通黏度计中流动时，雷诺数可能会很高，然而只有雷诺数保持很小的值时，才能使运动保持层流形式，对于在多伦多所使用的测量圆柱振子阻尼的方法尤其是这样。但是多伦多实验并不满足这一条件，因此推导出来的黏度值应该对应于湍流运动，而这比真实值大多少都有可能。 [英文](#)

液氦II的动力黏度很小，这就使得测量其黏度比较困难。为尽量保持层流，我们设计出了如下实验方法（见附图）。利用液体流经圆盘1

和2之间空隙时的压强差可以测得黏度；其中两个圆盘是用玻璃制成的，并且是光学级平整的，它们之间的空隙可以利用云母隔离片进行调节。上面的圆盘1直径为3厘米，中间有一个直径1.5厘米的洞，洞上固定着一个玻璃管（3）。利用线（4）使这个装置在液氮中上升和下降，就可以令管3中液柱的水平位置高于或低于外围杜瓦瓶中液面（5）。利用测高计读出两液面之间的差，我们就可以推导出流量和压力的大小。

英文



英文

测量的结果相当明显。当两盘之间没有隔离片时，即令盘1和2接触（通过光学条纹的观测，估计其间距约为半微米），液氮流在高于 λ 点时需要经过几分钟才勉强能检测到，而在低于 λ 点时，液氮流动非常容易，管3中的液面在几秒钟内就稳定下来了。从这些测量我们可以推断，常压下氦II的黏度是氦I的1,500分之一。

英文

实验还显示，氦II穿过空隙时的压强差正比于流动速度的平方，这表明这种流动一定是湍流。但是，如果我们假设它以层流的形式运动，并计算它的黏度，得到数量级为 10^{-9} 单位（厘米克秒制）的值，显然，这只是真实值的上限。按照这种估计，尽管间隙如此小，雷诺数仍然超过了50,000这个肯定会出现湍流的数值。

英文

我们还在继续实验工作，期望进一步减小液氮II的黏度上限值，但

是目前的上限（即 10^{-9} 单位（厘米克秒制））已经非常小了，因为它最多是氢气（过去认为是黏度最小的流体）黏度的 $1/10^4$ 。目前得到的极限也许足以表明，与超导体进行类比，氦在低于 λ 点时会进入一种特殊的状态，我们不妨称之为“超流体”。 [英文](#)

如同我们之前提到的那样，我们的实验中显示的异常低的黏度，可能确实可以用来解释高热导率，以及由艾伦、佩尔斯和乌丁^[2]所观测到的其他异常性质。在对液氦II进行所需的技术操作过程中，由于其具有较大的流动性，因此湍流的出现显然是无法避免的，即便在用于测量热导率的小毛细管中；而这种湍流运动将通过对流效率极高地传输热。

[英文](#)

（王耀杨 翻译；于渌 审稿）

Flow of Liquid Helium II

J. F. Allen and A. D. Misener

In Cambridge, physicists John Allen and Don Misener had come to the same conclusion as Kapitza (see the previous paper). As they announce here, they had also attempted to measure the viscosity of liquid helium below the so-called “lambda point” of 2.18 K in experiments where the fluid flowed through narrow capillaries. But their results could only place an upper limit on the viscosity, comparable to Kapitza’s value. They note that the flow they observed is very strange, being independent of the pressure difference applied. It is possible, they speculate, that the liquid is actually slipping over the surface. These results would later be explained by a general theory of liquid helium as a superfluid, a state that arises from quantum-mechanical behaviour. [中文](#)

A survey of the various properties of liquid helium II has prompted us to investigate its viscosity more carefully. One of us¹ had previously deduced an upper limit of 10^{-5} C.G.S. units for the viscosity of helium II by measuring the damping of an oscillating cylinder. We had reached the same conclusion as Kapitza in the letter above; namely, that due to the high Reynolds number involved, the measurements probably represent non-laminar flow. [中文](#)

The present data were obtained from observations on the flow of liquid helium II through long capillaries. Two capillaries were used;

the first had a circular bore of radius 0.05 cm. and length 130 cm. and drained a reservoir of 5.0 cm. diameter; the second was a thermometer capillary 93.5 cm. long and of elliptical cross-section with semi-axes 0.001 cm. and 0.002 cm., which was attached to a reservoir of 0.1 cm. diameter. The measurements were made by raising or lowering the reservoir with attached capillary so that the level of liquid helium in the reservoir was a centimetre or so above or below that of the surrounding liquid helium bath. The rate of change of level in the reservoir was then determined from the cathetometer eye-piece scale and a stopwatch; measurements were made until the levels became coincident. The data showing velocities of flow through the capillary and the corresponding pressure difference at the ends of the capillary are given in the accompanying table and plotted on a logarithmic scale in the diagram.

中文

Capillary I		Capillary II			
$T=1.07^{\circ}\text{K.}$		$T=1.07^{\circ}\text{K.}$		$T=2.17^{\circ}\text{K.}$	
Velocity (cm./sec.)	Pressure (dynes)	Velocity (cm./sec.)	Pressure (dynes)	Velocity (cm./sec.)	Pressure (dynes)
13.9	183.5	8.35	402	0.837	36.6
11.5	154.5	6.92	218	0.757	31.3
10.3	127.7	6.88	143	0.715	26.1
9.0	105.0	6.30	101	0.685	21.1
8.2	83.5	6.05	56	0.655	16.4
7.5	65.7	5.55	30	0.609	12.1
6.9	49.3	4.70	11.3	0.570	8.3
6.1	34.1	4.39	9.2	0.525	4.3
5.2 ⁵	20.3	3.92	13.0	0.433	0.9
4.5 ⁵	15.2	2.88	7.2		

中文

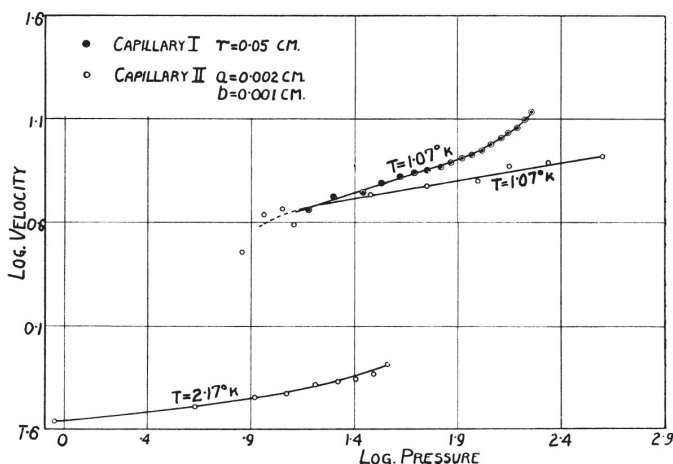
The following facts are evident:

(a) The velocity of flow, q , changes only slightly for large changes in pressure head, p . For the smaller capillary, the relation is approximately $p \propto q^6$, but at the lowest velocities an even higher power seems indicated.

中文

(b) The velocity of flow, for given pressure head and temperature, changes only slightly with a change of cross-section area of the order of 10^3 . 中文

(c) The velocity of flow, for given pressure head and given cross-section, changes by about a factor of 10 with a change of temperature from 1.07°K . to 2.17°K . 中文



中文

(d) With the larger capillary and slightly higher velocities of flow, the pressure-velocity relation is approximately $p \propto q^3$, with the power of q decreasing as the velocity is increased. 中文

If, for the purpose of calculating a possible upper limit to the viscosity, we assume the formula for laminar flow, that is, $p \propto q$, we obtain the value $\eta = 4 \times 10^{-9}$ C.G.S. units. This agrees with the upper limit given by Kapitza who, using velocities of flow considerably higher than ours, has obtained the relation $p \propto q^2$ and an upper limit to the viscosity of $\eta = 10^{-9}$ C.G.S. units. 中文

The observed type of flow, however, in which the velocity becomes almost independent of pressure, most certainly cannot be treated as laminar or even as ordinary turbulent flow. Consequently any known

formula cannot, from our data, give a value of the “viscosity” which would have much meaning. It may be possible that the liquid helium II slips over the surface of the tube. In this case any flow method would be incapable of showing the “viscous drag” of the liquid. 中

文

With regard to the suggestion that the high thermal conductivity of helium II might be explained by turbulence, we have calculated that the flow velocity necessary to transport all the heat input over the observed temperature gradient in the Allen, Peierls and Uddin experiments² is about 10^4 cm./sec. On the other hand, the greatest flow velocity produced by manipulation and by the pressure difference along the thermal conduction capillary will not be likely to be greater than 50 cm./sec. It seems, therefore, that undamped turbulent motion cannot account for an appreciable part of the high thermal conductivity which has been observed for helium II. 中文

(141, 75; 1938)

J. F. Allen and A. D. Misener: Royal Society Mond Laboratory, Cambridge, Dec, 22.

References:

1. Burton, E.F., *Nature*, **135**, 265 (1935).
2. Allen, Peierls and Uddin, *Nature*, **140**, 62 (1937).

液氦II的流动

艾伦，麦色纳

在剑桥，物理学家约翰·艾伦和冬·麦色纳得出了与卡皮查相同的结论（见前一篇文章）。正如他们在这篇文章中介绍的，他们利用液体流过毛细管的实验，也试图去测量低于“ λ 点”（2.18 K）时液氦的黏度。但是与卡皮查的测量值相比，他们的结果仅仅得出了黏度值的上限。他们注意到他们观察到的流动现象非常奇特，它与两端施加的压力差无关。他们推测液体实际上是掠过表面。后来液氦超流态的普遍理论成功解释了这些现象，这是一种源于量子力学行为的状态。

[英文](#)

对液氦II各种性质的探索促使我们更细致地研究它的黏度。本文作者之一^[1]曾经通过测定振动圆柱的阻尼推导出液氦II黏度的上限为 10^{-5} 单位（厘米克秒制）。我们得到的结论与卡皮查在前文中叙述的相同；也就是说，由于测量过程中雷诺数很高，这一测量可能反映的是非层流的流动形式。

[英文](#)

本文的数据是通过观测液氦II在长毛细管中的流动获得的。其间用到了两种毛细管；第一种毛细管带有一个半径为0.05厘米、长为130厘米的圆形孔道，并与一个直径为5厘米的储液管相接；第二种毛细管是温度计毛细管，长93.5厘米，具有椭圆形的横截面，其半轴长分别为0.001厘米和0.002厘米，整个毛细管与直径为0.1厘米的储液管相连。测量方法是：将连接毛细管的储液管上下移动，以便于使储液管中的液氦平面位于周围液氦平面的上方或下方约1厘米处。利用测高计的目镜刻度和秒表便可确定储液管中液面的移动速率；当内外液面一致时即可停止测量。附表中数据显示了流经毛细管时的速度和相应的毛细管两端的压力差，对它们分别取对数绘于图中。

[英文](#)

毛细管 I		毛细管 II			
$T = 1.07\text{ K}$		$T = 1.07\text{ K}$		$T = 2.17\text{ K}$	
速度 (厘米 / 秒)	压力 (达因)	速度 (厘米 / 秒)	压力 (达因)	速度 (厘米 / 秒)	压力 (达因)
13.9	183.5	8.35	402	0.837	36.6
11.5	154.5	6.92	218	0.757	31.3
10.3	127.7	6.88	143	0.715	26.1
9.0	105.0	6.30	101	0.685	21.1
8.2	83.5	6.05	56	0.655	16.4
7.5	65.7	5.55	30	0.609	12.1
6.9	49.3	4.70	11.3	0.570	8.3
6.1	34.1	4.39	9.2	0.525	4.3
5.2 ⁵	20.3	3.92	13.0	0.433	0.9
4.5 ⁵	15.2	2.88	7.2		

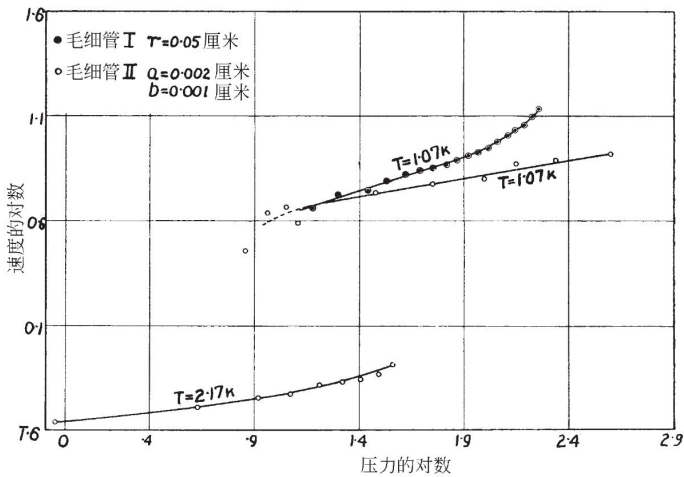
英文

从上表明显可以看出：

(a) 当压位差 p 大幅度改变时，流动速度 q 的变化不大。对于较细的毛细管，二者之间的关系近似为 $p \propto q^6$ ，但是在速度最低的时候，幂次似乎更高。 英文

(b) 对于给定的压位差和温度，当横截面面积以 10^3 数量级变化时，流动速度只发生微小的改变。 英文

(c) 对于给定的压位差和确定的横截面，在温度从1.07 K变化到2.17 K的过程中，流动速度变化了10倍左右。 英文



(d) 在较粗的毛细管中，对于略高的流动速度，压力 - 速度之间的关系近似为 $p \propto q^3$ ，其中 q 的幂次随速度增加而降低。 英文

为了计算出黏度的可能上限，我们假定层流运动的计算公式即 $p \propto q$ 成立，那么就可以得到 $\eta = 4 \times 10^{-9}$ 单位（厘米克秒制）。这个结果与卡皮查给出的上限是一致的，因为他使用的流动速度比我们所用的高很多，所以得出的关系式为 $p \propto q^2$ ，他最后给出的黏度上限是 $\eta = 10^{-9}$ 单位（厘米克秒制）。 英文

不过，当流动速度与压力无关时，我们所观测到的这种流动类型一定不属于层流，甚至不属于普通的湍流。因此，根据我们的测量数据任何已知的公式都不可能给出一个很有意义的“黏度”数值。液氦II可能掠过管壁，在这种情况下，任何流动方法都无法显示出液体的“黏滞阻力”。 英文

有人认为用湍流也许能够解释氦II的高热导率，对此我们计算的结果是，只有流速大约为 10^4 厘米/秒左右时，才足以在艾伦、佩尔斯和乌丁的实验^[2]中观测到的温度梯度条件下传输所有输入的热量。而另一方面，在实验操作下沿着热传导毛细管的压力差所能产生的最大流速可能不会超过50厘米/秒。由此看来，无衰减的湍流运动并不能解释在氦II中观测到的高热导率。 英文

（王耀杨 翻译；于渌 审稿）

The λ -phenomenon of Liquid Helium and the Bose–Einstein Degeneracy

F. London

In early 1938, *Nature* published the first reports of superfluidity in liquid helium, discovered independently by Pyotr Kapitza in Russia and by John Allen and Don Misener at Cambridge. Both reported that when cooled below 2.17 K, the viscosity of the liquid plunged apparently to zero. One proposed explanation was that the helium atoms adopted an ordered structure like that of diamond crystals. Here Fritz London proposes a radically different idea: that the phenomenon might be linked to the low-temperature quantum behaviour of particles of integer spin (“bosons”), whose collective statistical behaviour had been described by Bose and Einstein. [中文](#)

IN a recent paper¹ Fröhlich has tried to interpret the λ -phenomenon of liquid helium as an order–disorder transition between n holes and n helium atoms in a body-centred cubic lattice of $2n$ places. He remarks that a body-centred cubic lattice may be considered as consisting of two shifted diamond lattices, and he assumes that below the λ -point the helium atoms prefer the places of one of the two diamond lattices. The transition is treated on the lines of the Bragg–Williams–Bethe theory as a phase transition of second order in close analogy to the

transition observed with β -brass. Jones and Allen in a recent communication to *Nature*² also referred to this idea. In both these papers, use is made of the fact, established by the present author, that with the absorbed abnormally great molecular volume of liquid helium (caused by the zero motion³) the diamond-configuration has the lowest potential energy among all regular lattice structures⁴.

中文

In this note, I should like first to show that the mechanism proposed by Fröhlich cannot be maintained and then to direct attention to an entirely different interpretation of this strange phenomenon. 中文

(1) According to Fröhlich, a diamond lattice of He atoms, when partly formed, should offer, to any other He atom, a preference for being attached at those points which belong to the same diamond lattice, that is, the binding energy at a diamond point should be greater than anywhere else. It is, however, easy to see that just those points, which according to Fröhlich should become less favoured for low temperatures, have an appreciably greater binding energy. It is true these holes have four nearest neighbours at exactly the same distance (3.08 Å), as the lattice points of the diamond lattice have, but in addition they possess six second neighbours at the distance of 3.57 Å. which the diamond lattice points do not possess, and these second neighbours contribute considerably to the binding energy just at the hole-places (about 50 percent to the potential energy). Therefore, actually no such co-operative phenomenon will appear as supposed by Fröhlich. The atoms would rather frequent the holes as much as the proper diamond lattice points, and this would signify that we have a body-centred lattice of $2n$ places for n atoms, every place being occupied with the probability $\frac{1}{2}$ only—even at the absolute zero. In this configuration every atom has on the average four nearest neighbours at a distance of 3.08 Å, as in the diamond configuration, but in addition there are here on the average three second neighbours

at the distance of 3.57 Å. In the diamond lattice there are twelve second neighbours but at a distance of 5.04 Å., where there is almost no Van der Waals field. It might be mentioned, by the way, that a face-centred lattice of $2n$ places for n atoms (on the average 6 first neighbours at a distance of 3.17 Å.) has been found to have a still little lower energy than the configuration just discussed of the co-ordination number 4. [中文](#)

Complete numerical details cannot be given here; in any event it can be shown by such energetic discussions that a static spatial model of liquid He II of whatever regular configuration is certainly not possible. This has been previously suggested in consideration of the great zero point amplitude calculated for He⁴. The determination of the most favourable co-ordination numbers of the first and second neighbours, however, maintains a good physical meaning: it may be considered as a rough Hartree calculus which yields the self-consistent field and the corresponding probability distribution of the atoms belonging to the minimum of energy. [中文](#)

(2) It seems, therefore, reasonable to imagine a model in which each He atom moves in a self-consistent periodic field formed by the other atoms. The different states of the atoms may be described by eigen functions of a similar type to the electronic eigen functions which appear in Bloch's theory of metals; and, as in Bloch's theory, the energy of the lowest states will roughly be represented by a quadratic function of the wave number K ,

$$E = \frac{\hbar^2}{2m^*} K^2,$$

the effective mass m^* being of the order of magnitude of the mass of the atoms. But in the present case we are obliged to apply Bose-Einstein statistics instead of Fermi statistics. [中文](#)

(3) In his well-known papers, Einstein has already discussed a peculiar

condensation phenomenon of the “Bose–Einstein” gas; but in the course of time the degeneracy of the Bose–Einstein gas has rather got the reputation of having only a purely imaginary existence. Thus it is perhaps not generally known that this condensation phenomenon actually represents a discontinuity of the derivative of the specific heat (phase transition of third order). In the accompanying figure the specific heat (C_v) of an *ideal* Bose–Einstein gas is represented as a function of T/T_0 where

$$T_0 = \frac{h^2}{2\pi m^*k} \left(\frac{n}{2,615}\right)^{2/3},$$

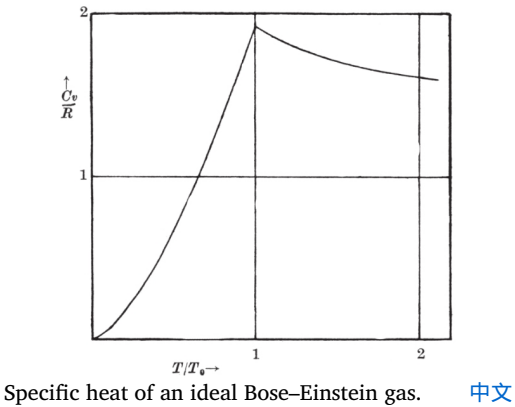
With m^* = the mass of a He atom and with the mol. volume $\frac{N_1}{n} = 27.6$ cm.³ one obtains $T_0 = 3.09^\circ$. For $T \leq T_0$ the specific heat is given by

$$C_v = 1.92 R(T/T_0)^{3/2}$$

and for $T \geq T_0$ by

$$C_v = \frac{3}{2} R \left[1 + 0.231 \left(\frac{T_0}{T}\right)^{3/2} + 0.046 \left(\frac{T_0}{T}\right)^3 + \cdots \right]$$

The entropy at the transition point T_0 amounts to $1.28 R$ independently of T_0 . 中文



(4) Though actually the λ -point of helium resembles rather a phase transition of second order, it seems difficult not to imagine a

connexion with the condensation phenomenon of the Bose–Einstein statistics. The experimental values of the temperature of the λ -point (2.19°) and of its entropy ($\sim 0.8 \text{ } R$) seem to be in favour of this conception. On the other hand, it is obvious that a model which is so far away from reality that it simplifies liquid helium to an ideal gas, cannot, for high temperatures, yield but the value $C_v = 3/2 \text{ } R$, and also for low temperatures the ideal Bose–Einstein gas must, of course, give too great a specific heat, since it does not account for the gradual “freezing in” of the Debye frequencies. [中文](#)

According to our conception the quantum states of liquid helium would have to correspond, so to speak, to both the states of the electrons and to the Debye vibrational states of the lattice in the theory of metals. It would, of course, be necessary to incorporate this feature into the theory before it can be expected to furnish quantitative insight into the properties of liquid helium. [中文](#)

The conception here proposed might also throw a light on the peculiar transport phenomena observed with HeII (enormous conductivity of heat⁵, extremely small viscosity⁶ and also the strange fountain phenomenon recently discovered by Allen and Jones²). [中文](#)

A detailed discussion of these questions will be published in the *Journal de Physique*. [中文](#)

(141, 643-644; 1938)

F. London: Institut Henri Poincaré, Paris, March 5.

References:

1. Fröhlich, H., *Physica*, **4**, 639 (1937).
2. Allen, J. F., and Jones, H., *Nature*, **141**, 243 (1938).
3. Simon, F., *Nature*, **133**, 529 (1934).
4. London, F., *Proc. Roy. Soc., A*, **153**, 576 (1936).
5. Rollin, *Physica*, **2**, 557 (1935); Keesom, W. H., and Keesom, H. P. *Physica*, **3**, 359 (1936); Allen, J. F., Peierls, R., and Zaki Uddin, M., *Nature*, **140**, 62 (1937).

6. Burton, E. F., *Nature*, **135**, 265 (1935); Kapitza, P., *Nature*, **141**, 74 (1938); Allen, J. F. and Misener, A. D., *Nature*, **141**, 75 (1938).

液氦的 λ 现象和玻色-爱因斯坦简并

伦敦

1938年初,《自然》刊载了两篇有关液氦超流动性的最早报告,那是俄国的彼得·卡皮查和剑桥的约翰·艾伦与冬·麦色纳各自独立发现的。两篇文章都提到当温度低于2.17 K时液氦的黏度似乎减小至零。有人认为这是由于氦原子排列成为类似金刚石晶体那样的有序结构。而这篇文章中弗里茨·伦敦提出了一个完全不同的看法:这种现象也许与某些具有整数自旋的粒子(“玻色子”)在低温下的量子力学行为有关,玻色和爱因斯坦曾经对玻色子的统计行为进行过描述。 [英文](#)

弗勒利希最近的一篇文章中^[1]试图将液氦的 λ 现象解释为在一个具有 $2n$ 个位置的体心立方晶格中, n 个空位和 n 个氦原子间的有序-无序相变。他认为,可以把一个体心立方晶格看作是由两套具有相对位移的金刚石晶格组合而成的,而且他假定在低于 λ 点时,氦原子更倾向于处在两套金刚石晶格中某一套的格点上。根据布拉格-威廉姆斯-贝特理论,这种转变被看作是一种二阶相变,非常类似于在 β 黄铜中发生的相变。琼斯和艾伦最近给《自然》的信^[2]中也提到了这一观点。在这两篇文章中,都用到了本文作者确认的事实,即由于液氦占有的分子体积异常大(源于零点运动^[3]),所以在所有规则结构的晶格中,金刚石结构具有最低的势能^[4]。 [英文](#)

在这篇短文中,我首先会说明弗勒利希提出的机制是不成立的,然后再引导大家关注对这种奇异现象的一种完全不同的解释。 [英文](#)

(1) 按照弗勒利希的观点,当He原子的金刚石晶格部分形成时,对于其他的He原子而言,属于同一套金刚石晶格上的格点应该更有优势,也就是说,金刚石晶格上的结合能应该大于其他点处的结合能。然

而，我们很容易看出，按照弗勒利希的观点，在低温下对结合较为不利的那些位点反而具有比其他位点高得多的结合能。晶格中的空位在完全相同的距离（3.08埃）处有4个最近邻，这与金刚石晶格的格点相同，但不同的是它们在距离3.57埃处还有6个次近邻，而且这些次近邻对空位的结合能贡献是很大的（约占势能的50%）。因此，弗勒利希提出的这种合作现象是不会发生的。原子不仅易处于金刚石晶格的格点上，而且更易处于空位上，这意味着对于 n 个原子来说，我们有 $2n$ 个位置的体心立方格子，每个位置被占据的概率即使在绝对零度下也仅为 $1/2$ 。每个原子在距离3.08埃处平均有4个最近邻，这与金刚石晶格结构相同，但除此之外，每个原子在距离3.57埃处平均还有3个次近邻。而在金刚石晶格中有12个次近邻，但距离是5.04埃，几乎没有范德瓦尔斯场。顺便提一下，对于 $2n$ 个位置， n 个原子的面心立方晶格（在距离3.17埃处平均有6个最近邻），其能量略低于刚才讨论过的配位数为4的结构。

英文

在本文中我们不可能给出完整的数值计算过程；但是，通过对这种能量的讨论可以阐明，液体He II任何规则结构的静态空间分布模型肯定都是不可能的。这点在计算He巨大的零点振幅时就被提出^[4]。然而，确定最近邻和次近邻的最佳配位数却有着清楚的物理意义，其可以看作是粗略的哈特里计算，由此我们可得到自洽场和相对应的处于能量极小值的原子的分布概率。

英文

（2）因此似乎可以构造这样一个模型，其中每个He原子在其他原子形成的自洽周期场中运动。用本征函数来描述原子不同的态，类似于在布洛赫的金属理论中用电子本征函数描述电子态；而且，类似于布洛赫理论，最低态的能量可以粗略地表示为波矢 K 的二次函数，

$$E = \frac{\hbar^2}{2m^*} K^2$$

其中有效质量 m^* 与原子质量的数量级相当。不过我们现在必须用玻色-爱因斯坦统计代替费米统计。

英文

（3）在一些著名的文章中，爱因斯坦已经讨论了“玻色-爱因斯坦”气体特有的一种凝聚现象；但是，随着时间的推移，人们开始认为玻

色-爱因斯坦气体的简并性不过是一种假象。因此可能很多人并不知道这种凝聚现象实际上表现为比热的导数的不连续（三阶相变）。在附图中，理想玻色-爱因斯坦气体的比热（ C_v ）可表示为 T/T_0 的函数，

$$T_0 = \frac{h^2}{2\pi m^* k} \left(\frac{n}{2,615} \right)^{2/3}$$

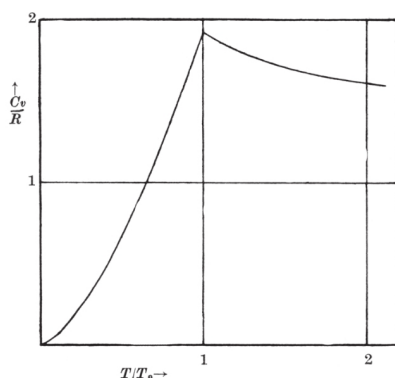
式中取 $m^* = \text{He的原子质量}$ ，摩尔体积 $\frac{N_l}{n} = 27.6$ 立方厘米，可得 $T_0 = 3.09 \text{ K}$ 。对于 $T \leq T_0$ ，所给出的比热为：

$$C_v = 1.92 R (T/T_0)^{3/2}$$

对于 $T \geq T_0$ ，比热为：

$$C_v = \frac{3}{2} R \left[1 + 0.231 \left(\frac{T_0}{T} \right)^{3/2} + 0.046 \left(\frac{T_0}{T} \right)^3 + \dots \right]$$

在转变点 T_0 ，熵为 $1.28R$ ，与 T_0 无关。 [英文](#)



理想玻色-爱因斯坦气体的比热变化关系 [英文](#)

（4）尽管氦的 λ 点实际上更类似于一种二阶相变，但还是很容易将其与玻色-爱因斯坦统计的凝聚现象联系起来。 λ 点处的温度（ 2.19 K ）和熵（ $\sim 0.8R$ ）的实验值似乎支持了这一猜想。另一方面，我们可以很明显地看出，把液氮简化为一种理想气体是一个脱离实际的模型，这个模型在高温时只能给出 $C_v = 3/2R$ ，而在低温区，理想的玻色-爱因斯坦气体也必然会给出过大的比热值，因为此模型并没有考虑德拜频率的逐渐“冻结”。 [英文](#)

按照我们的构想，可以说液氦的量子态既对应于金属理论中的电子态又对应于晶格的德拜振动态。当然，我们必须要把这个特点涵盖在理论中，才能有望对液氦的性质有定量的了解。 [英文](#)

本文提出的构想或许对理解HeII中特别的输运现象有一点启发（巨大的热导率^[5]，极小的黏度^[6]，以及最近艾伦和琼斯观察到的奇异的喷泉现象^[2]）。 [英文](#)

有关这些问题的详细讨论将发表在《物理学杂志》上。 [英文](#)

（沈乃澂 翻译；于渌 审稿）

Mesotron (Intermediate Particle) as a Name for the New Particles of Intermediate Mass

C. D. Anderson and S. H. Neddermeyer

In 1936, Carl Anderson and Seth Neddermeyer at the California Institute of Technology found evidence in cosmic-ray experiments for a particle having mass intermediate between those of the electron and proton. The particle carried one unit of charge, and penetrated matter much more strongly than the electron. Here the particle's discoverers propose a name for it. As its intermediate mass seemed the key property, they suggest the term "mesotron". This was later shortened to "meson", although the particle Anderson and Neddermeyer had discovered was actually what physicists today call the muon, a massive relative of the electron. The term meson later became used for intermediate-mass "hadrons" such as the pion or kaon, which are comprised of two quarks. [中文](#)

THE existence of particles intermediate in mass between protons and electrons has been shown in experiments on the cosmic radiation¹. Since at present so little is known concerning the properties of these particles, for example, the exact value of the mass, the laws governing their production, their stability against disintegration, etc., it may yet be too early to assign to them a name. But inasmuch as several names

have already been suggested, namely, dynatron, penetron, barytron, heavy electron, yukon and x-particle, it may be wise to consider the matter at this time. [中文](#)

The property which so far serves to distinguish the new particles from the other two types of particles which carry the same magnitude of electric charge, namely, the proton and the electron, seems to be the magnitude of their mass. Although from the experiments so far performed, it is not possible to say definitely whether the new particles exist with a unique mass only, or whether they occur with a range of masses, it does appear quite certain that the mass, whether unique or not, is greater than that of an electron and less than that of a proton. One must consider then three types of particles all carrying electric charges of equal magnitude: electrons, the new particles and protons. We should like to suggest therefore the word “mesotron” (intermediate particle) as a name for the new particles. It appears quite likely that the appropriateness of this name will not be lost, whatever new facts concerning these particles may be learned in the future. [中文](#)

(142, 878; 1938)

Carl D. Anderson and Seth H. Neddermeyer: California Institute of Technology, Pasadena, Sept. 30.

Reference:

1. For historical summary see Wentzel, G., *Naturwiss.*, **26**, 273 (1938); and Bowen, Millikan and Neher, footnote, *Phys. Rev.*, **53**, 219 (1938).

将介子（中间粒子）定为一种中间质量新粒子的名字

安德森，尼德迈耶

1936年，美国加州理工学院的卡尔·安德森和塞思·尼德迈耶在宇宙射线实验中发现了一种质量介于电子和质子之间的粒子的径迹。这种粒子携带一个单位的电荷，穿透能力比电子强。本文中粒子的发现者提出为它命名。鉴于它的质量介于电子和质子之间是其重要性质，故建议选用单词“mesotron”，之后被缩写成“meson”，而安德森和尼德迈耶所发现的粒子实际上是今天物理学家所指的与电子有近亲关系的 μ 介子。介子（meson）一词后来用于表示中间质量的“强子”，例如由两个夸克组成的 π 介子和K介子。 [英文](#)

在宇宙射线实验中发现了一种新粒子，其质量介于质子和电子之间^[1]。目前，人们对这种粒子的性质，例如粒子质量的精确值、产生的机制、对衰变的稳定性等了解甚少。因此现在给它们确定一个名字也许为时过早。但是，因为大家已经提出了几个候选的名字：（朝）代子、穿（透）子、重子、重电子、汤川子以及x粒子，所以也许现在来考虑这个问题是必要的。 [英文](#)

迄今为止，只能通过质量的数值来区分这种新粒子与其他两种粒子——即携带相同数量电荷的质子和电子。虽然根据目前已做的实验尚无法肯定这种新粒子的质量是否有一个确定值，还是在一定的范围内变化，但可以肯定它们的质量，无论其数值是否唯一，都是大于电子而小于质子的，故可以认为三种类型的粒子，即电子、新粒子和质子，都带有相同数量的电荷。所以，我们建议用“mesotron”（中间粒子）作为这种新粒子的名称，这主要是因为我们认为这个名字的适用性不会因为将来发现了有关这个粒子的新性质而失效。 [英文](#)

(胡雪兰 翻译 ; 厉光烈 审稿)

New Broadcasting System

An engineer in the United States, *Nature* reports here, has developed a new kind of radio broadcasting system. Radio systems at that time worked by amplitude modulation, which encodes the signal, such as voice, in modulations of the amplitude of the carrier wave. In contrast, the new system developed by Edwin Armstrong encodes information in modulations of the frequency of the carrier wave. That gave a sharp reduction in radio interference, although there was a considerable increase in the receiver's complexity. Although the basic principles of this scheme of frequency modulation, or FM radio, had long been known, Armstrong brought it to fruition with valves and circuits. The first transmitting station, in Alpine New Jersey, began operating soon after.

中文

ACCORDING to a recent report by the New York Correspondent of *The Times*, a new type of wireless transmission and reception will be used in an experimental station now being erected at Columbia University by Major E. H. Armstrong, professor of electrical engineering in the University, and inventor of the now well-known supersonic-heterodyne receiver. The station will use the frequency-modulation system of transmission, as distinct from the amplitude-modulation system at present used by all broadcasting stations. In the former method, the frequency of the emitted carrier wave is varied by the speech and music modulation; whereas in the methods so far employed, the frequency of the carrier wave remains constant and its

amplitude is varied by the applied audio-frequencies. The principles of frequency-modulation have been known since the earliest days of radio-telephony, but it has remained for Prof. Armstrong to demonstrate how these may be brought into practical use with modern valves and circuit arrangements. Among the advantages claimed for the new system are that it effects a considerable reduction of interference in radio reception, and that a much larger number of broadcasting channels will become available in any given wave-length band. Against these, however, is the serious disadvantage that special receivers are necessary for frequency-modulated transmissions, and this factor is likely to involve serious delay in the introduction of the new system into modern broadcasting technique. The first transmitting station on the new system will be at Alpine, New Jersey, opposite New York City, and it has a licence to broadcast on a frequency of 40 megacycles per second (wave-length 7.5 metres). It is also understood that suitable receivers are already being manufactured, so that the result of this practical experiment will be awaited with interest. [中文](#)

(143, 152; 1939)

新的广播系统

《自然》的这篇文章对一位美国工程师发展出的一套新的广播系统进行了报道。当时的广播系统是通过调幅，即对载波的振幅进行调制而将声音等信号进行编码的。与之相对应的是埃德温·阿姆斯特朗研制的新系统，该系统通过对载波的频率进行调制而编码信息。尽管增加了接收机的复杂程度，但这一技术大大降低了广播信号间的相互干扰。虽然人们早已经了解了调频（FM）广播的基本原理，但是阿姆斯特朗用电子管和线路将这一理论变成了现实。第一个采用这种技术的发射台不久将在新泽西州的阿尔派投入使用。 [英文](#)

根据《泰晤士报》驻纽约记者最新的一则报道，一家实验电台将采用一套新型的无线发射和接收系统，该实验电台目前正由哥伦比亚大学电子工程系教授阿姆斯特朗少校在该校架设，阿姆斯特朗教授也是目前广为人知的超外差接收器的发明者。目前所有广播电台使用的都是调幅系统，与此不同的是，正在建设中的这座电台将使用调频发射系统。在调频系统中，发射载波的频率会随着语音和音乐的声调变化而变化，而在目前使用的调幅系统中，载波的频率是恒定不变的，其振幅则随着所用音频的变化而变化。在无线电话问世之初，人们就已经知道了调频的原理。但是在阿姆斯特朗教授之前，没有人知道如何利用现代的电子管和各种电路元件将其带向实际应用。新系统的优点是：它大大减少了无线电接收中存在的干扰，也大幅增加了在任意给定的波长范围内可用的广播频道。然而，这种系统也有严重的缺点，人们必须用特殊的接收机才能接收调频发射的无线电信号，这一缺点很可能会严重减缓现代广播系统中应用这种新系统的速度。使用这种新系统的第一家发射台将设在新泽西州的阿尔派（与纽约市隔河相望），该发射台已经获得了在每秒40兆周（即波长7.5米）的频率上进行广播的授权。据悉，合适的接收机正在生产中，因此，大家都在饶有兴趣地等待着这项应用性实验的结

果。 英文

(刘霞 翻译；赵见高 审稿)

Interpretation of Beta-disintegration Data

H. A. Bethe *et al.*

Enrico Fermi had recently proposed a theory for radioactive beta decay. As Hans Bethe and colleagues point out here, the theory disagrees with experimental data by predicting, for example, too few electrons emerging at low energies. An alternative theory, while accounting for this feature, introduces other problems. Yet a resolution, the authors suggest, may lie in supposing that Fermi's theory is correct but that experiments so far have not observed simple radioactive decays but instead mixed together decay processes leading to different nuclear states. Evidence for this idea might be found by scrutinizing the gamma rays emitted during beta decays. [中文](#)

FERMI'S original theory of β -decay¹ made a definite prediction as to the energy distribution of the electrons emitted from a β -active element. It was found² that the experimental distribution curves did not agree in shape with this prediction in the sense that the number of electrons of low energy (relative to the upper limit of the spectrum) was considerably greater in the experimental than in the theoretical curves. A modified theory was then proposed by Konopinski and Uhlenbeck (K.U.)³ which introduced in the distribution curve another factor proportional to the square of the momentum of the emitted neutrino. This theory appeared to agree with the facts. [中文](#)

Further experimental evidence, however, revealed a number of facts which did not fit in well with the modified theory: (1) The shape of the observed energy spectra did not fit the K.U. law near the upper limit, but seemed there to follow the original law of Fermi, although the latter did not fit with any other part of the curve⁴; if one determined the position of the upper limit by extrapolation from the K.U. law, one obtained values that were difficult to reconcile either with the observed spectrum or with the other data on the energy balance⁵. (2) The Sargent curves (decay constant against disintegration energy) seemed to agree better with the Fermi theory⁴. (3) The probability of capturing a *K*-electron, as compared to that of emitting a positron, was found to be much smaller than the K.U. theory would predict, but in reasonable agreement with the Fermi theory⁶. (4) An attempt to develop the K.U. theory into a mathematically consistent scheme showed that it was, at any rate, far more complicated than that of Fermi, and no proof has as yet been given that it can be consistently carried further than to the first order of approximation⁷. 中文

We therefore investigated the view that the original theory of Fermi correctly represents the elementary law; but that the observed spectra, in so far as they belong to “allowed” transitions, do not represent the effect of a single nuclear transformation, but rather a superposition of different spectra belonging to transitions to different levels of the final nucleus. It is then clear that the resulting energy distribution will contain rather more electrons of low energies, compared to the upper limit of the spectrum, than a single Fermi curve. If the nucleus is left in an excited state, it must eventually lose its energy by radiation, and the crucial test for the suggested point of view is the presence of γ -rays of suitable energy and intensity from all those radioactive bodies which have “allowed” transitions and the energy spectra of which are known to be different from the simple Fermi curve. The γ -rays might in some cases be absent because the excited state of the nucleus might

be a metastable isomer; but this could not be true for all such elements. The restriction to allowed transitions is necessary because in “forbidden” transitions the shape, even of a single curve, is affected by more complicated factors⁸. [中文](#)

Interpreting from this point of view the electron spectra of ^{12}B , ^{20}F , ^{17}F , ^{13}N , ^{15}O , as given by Fowler, Delsasso and Lauritsen⁹, we have estimated the energy and intensity of the γ -radiation to be expected. The results are given in the following table. [中文](#)

Active element	Product nucleus	Energy of γ -ray in Mv.	Number of γ -quanta per disintegration
^{12}B	^{12}C	5	0.5
^{20}F	^{20}Ne	2	0.7
^{13}N	^{13}C	0.27	0.8
^{15}O	^{15}N	0.5	0.4
^{17}F	^{17}O	0.9	0.6

No great accuracy is claimed for these results since the curve-fitting is very sensitive to the high-energy ends of the electron spectra, which are not very accurately known, and also because we have assumed that only one excited level is involved, whereas there might be more. [中文](#)

The presence of a γ -ray accompanying the disintegration of ^{13}N was indeed reported by Richardson¹⁰, who gave its energy as 0.3 Mv. A γ -radiation from ^{20}F was reported by Burcham and Smith¹¹, and measurements of the energy of this radiation, which are being made by Bower¹², indicate a value of about 2.2 Mv. Although γ -radiations of the predicted energies from the other elements of our table have not been reported, it is interesting to notice that an energy level in ^{17}O at 0.83 Mv. is known to exist, since it is excited in a number of other nuclear reactions^{11,13}, and similarly an excited state of ^{12}C at 4.3 Mv. is known¹³. We are indebted to Mr. P. I. Dee for this discussion of the experimental data. [中文](#)

Finally, we would like to point out that, although one cannot consider the above evidence as convincing confirmation of the point of view we

suggest, it is certainly incompatible with the K.U. theory, since the existence of γ -rays shows that the observed curves must be superpositions of at least two simple spectra, whereas their shapes are not such as could be represented as sums of two K.U. curves with endpoints differing by the energy of the γ -rays. 中文

(143, 200-201; 1939)

H. A. Bethe: Physics Department, Cornell University.

F. Hoyle: Emmanuel College, Cambridge.

R. Peierls: University, Birmingham.

References:

1. Fermi, E., *Z. Phys.*, **88**, 161 (1934).
2. Kurie, F. N. D., Richardson, J. R., and Paxton, H. C., *Phys. Rev.*, **49**, 368(1936).
3. Konopinski, E. J., and Uhlenbeck, G. E., *Phys. Rev.*, **48**, 7 (1935).
4. Richardson, H. O. W., *Proc. Roy. Soc., A*, **161**, 456 (1937).
5. Cockcroft, J. D., *Proc. Roy. Soc., A*, **161**, 540 (1937).
6. Walke, H. (in the Press).
7. Fierz, M., *Helv. Phys. Acta*, **10**, 123, (1937).
8. Hoyle, F., *Proc. Roy. Soc., A*, **166**, 249 (1938).
9. Fowler, W. A., Delsasso, L. A., and Lauritsen, C. C., *Phys. Rev.*, **49**, 569 (1936).
10. Richardson, J. R., *Phys. Rev.*, **53**, 610 (1938).
11. Burcham, W. E., and Smith, C. L., *Proc. Roy. Soc., A*, **168**, 176 (1938).
12. Private communication.
13. Cockcroft, J. D., and Lewis, W. B., *Proc. Roy. Soc., A*, **154**, 261 (1936).

对 β 衰变数据的解释

贝特等

恩里科·费米最近提出了放射性 β 衰变理论。正如汉斯·贝特和他的同事在这里所指出的，该理论的预言与实验结果不符，例如，预言认为几乎没有出现低能电子。另一种理论虽能解决这个难题，但却引入了其他问题。本文作者给出的解答是，不妨假定费米理论是正确的，只是迄今为止的实验还没有观测到简单的放射性衰变过程，而观测到的是混在一起的导致不同核状态的衰变过程。如果仔细检查 β 衰变中放出的 γ 射线，或许可以发现支持这一观点的证据。

英文

费米最初的 β 衰变理论^[1]明确地预言了从 β 放射性元素发射出的电子的能量分布。但是，人们发现^[2]实验中能量分布曲线的形状与费米理论的预言不一致：在能量分布实验曲线中，低能电子（相对于能谱上限来说）的数目明显多于理论预言值。因此，科诺平斯基与乌伦贝克^[3]对费米理论进行了修正（修正后的理论称为KU理论），他们在能量分布曲线中引入了一个与所放射的中微子的动量平方成正比的因子。修正后的理论似乎与实验结果相符。

英文

然而，进一步的实验证据揭示了很多与修正理论不符的现象：

（1）所观测到的能谱形状在上限附近虽与KU理论不符，却与费米的原始理论一致，但费米理论并不能与曲线的其他部分相吻合^[4]。如果通过KU理论推出上限位置，那么人们得到的值既难于与观察到的能谱吻合，也难于与基于能量平衡^[5]的其他一些数据吻合。（2）萨金特曲线（衰变系数依衰变能量变化的曲线）似乎与费米理论^[4]符合得更好。（3）和放射一个正电子的概率相比，俘获一个K电子的概率要远小于KU理论的预计，但是却在合理范围内与费米理论^[6]一致。（4）曾经有人尝试

进一步发展KU理论，以求达到数学形式上的一致，然而这比对费米理论进行相同的尝试要复杂得多，并且到目前为止仍然没有证据可以支持比一阶近似更高的精确度[7]。[英文](#)

因此，我们认为，费米的原始理论正确地表示了基本法则。但是，因为观测到的能谱属于“允许”跃迁，所以并不表示单核转变的结果，而是向末态原子核不同能级跃迁形成的不同能谱的叠加。这样就可以清楚地看出，能量分布结果包含的（相对能谱上限来说）低能电子比一条单峰费米曲线包含的更多。如果原子核处于激发态，它最终将通过辐射来释放能量，因此可以验证我们观点的关键实验现象包括：存在从所有具有“允许”跃迁的放射性物质中放射出的具有适当强度和能量的 γ 射线，以及与单峰费米曲线不同的能谱。在某些情况下， γ 射线也有可能不出现，因为原子核的激发态可能是一个亚稳的同质异能态，但是这种现象不可能对所有放射性元素都成立。对允许跃迁的限制是必要的，因为在“禁戒”跃迁中曲线的形状——即使是一条单峰曲线——都会受到更加复杂因素的影响[8]。[英文](#)

用以上观点来解释福勒、德尔萨索以及劳里森[9]给出的 ^{12}B 、 ^{20}F 、 ^{17}F 、 ^{13}N 和 ^{15}O 电子能谱，我们估算了 γ 辐射的能量和强度的期望值。下表给出了计算结果。[英文](#)

放射性元素	生成原子核	γ 射线能量, 单位兆电子伏	每次衰变辐射的 γ 量子数
^{12}B	^{12}C	5	0.5
^{20}F	^{20}Ne	2	0.7
^{13}N	^{13}C	0.27	0.8
^{15}O	^{15}N	0.5	0.4
^{17}F	^{17}O	0.9	0.6

我们没能给出非常精确的结果，因为曲线拟合对电子能谱的高能端非常敏感，而我们对此了解得又不够精确，并且我们在实验理论中假设只存在在一个激发态，而事实上可能存在很多激发态。[英文](#)

理查森[10]曾报道过关于 ^{13}N 衰变伴随有 γ 射线出现的现象，并且给出 γ 射线的能量是0.3兆电子伏。伯彻姆和史密斯[11]报道过 ^{20}F 的 γ 辐射，其能量值由鲍尔[12]测得，约为2.2兆电子伏。虽然我们在表中列出的其他元素 γ 辐射的能量期望值还没有相关的实验报道，但有趣的是， ^{17}O 的一个能级为0.83兆电子伏，这是已知存在的，因为它在其他很多核反应

中是激发态^[11,13]，类似地，¹²C一个能级为4.3兆电子伏的激发态也是已知的^[13]。我们非常感谢迪伊先生与我们讨论了这些实验数据。

英文

最后，需要指出的是，虽然不能将上述证据看作是对我们提出的观点的有力证明，但是这些证据肯定与KU理论不符，因为 γ 射线的存在表明观察到的曲线一定至少是两条单峰能谱的叠加，然而它们的形状并不是两条由于 γ 射线能量造成其端点不同的KU曲线的叠加。

英文

（王静 翻译；厉光烈 审稿）

Liquid Helium

J. F. Allen and H. Jones

One of the sensations of the late 1930s was the discovery of the strange properties of liquid helium II—a form of liquid helium that appears when the ordinary material is cooled below 2.19K. The Royal Society Mond Laboratory was established in the early 1930s at the Cavendish Laboratory in Cambridge by Ernest Rutherford, who planned that it should be the workplace of Pyotr Kapitza. By 1939, however, when this article appeared, Kapitza had returned to Moscow, taking with him much of the electromagnetic equipment the Mond Laboratory had contained. One striking feature of the measurement described in this article is that the viscosity of liquid helium falls sharply as it is converted into helium II. The current explanation is that liquid helium II owes its distinctive properties to quantum mechanics and that the bulk of the liquid exists in the form of a “Bose–Einstein condensate”—essentially the liquid moves as an integrated whole. [中文](#)

THE properties of liquid helium can best be considered under two headings: (a) properties in thermal equilibrium, (b) transport effects. The equilibrium properties, which have been the subject of many careful investigations in Leyden and elsewhere, may be regarded as fairly well established. These include the determination of the specific heat for different temperatures, the variation of density with

temperature at different constant pressures, and the relation of the saturated vapour pressure to the absolute temperature scale. The investigations of transport effects such as the flow of the liquid through tubes, heat conductivity and associated effects are still in an early stage of development, and no clear understanding of these phenomena has yet been reached. The subject was discussed at a meeting following the International Refrigeration Congress in July and also during the Cambridge meeting of the British Association. In this article we shall confine our attention largely to the interesting newly discovered transport effects, and give an account of recent experiments the results of which at present seem to find general acceptance. [中文](#)

Equilibrium Properties of Liquid Helium

Helium at atmospheric pressure liquefies at 4.22°K. ; the critical temperature is 5.2°K. Generally speaking, the temperature range over which the properties of liquid helium have been measured extends only down to 1°K. , since this is the lowest temperature conveniently reached by lowering the vapour pressure over the surface of the liquid. At 2.19°K. under its own vapour pressure, liquid helium undergoes a remarkable transformation. As the liquid is cooled through 2.19°K. , the specific heat jumps suddenly from a value of 0.4 cal. per gm. per degree to more than 5 cal. per gm. per degree, thereafter falling rapidly, approximately as T^5 . Simon has recently shown that at very low temperatures ($0.02^{\circ}\text{--}0.05^{\circ}\text{K.}$) produced by adiabatic demagnetization of iron ammonium alum, the specific heat of liquid helium varies as T^3 . [中文](#)

The transformation at 2.19°K. has also a remarkable effect on the expansion coefficient of liquid helium. Above that temperature it is positive, while below it is negative, although there is no discontinuity in the value of the density itself at 2.19°K. [中文](#)

Phase transformations of the type that liquid helium undergoes at 2.19°K. are known in other branches of physics; for example, the Curie-point transformation of a ferromagnetic, the order-disorder transformation of certain alloys, and the transition between the superconductive and the normal state of a metal. The temperature of the transformation in liquid helium is known as the λ -point, a name introduced by Ehrenfest. The modification of the liquid below the λ -point is generally referred to as helium II, that above the λ -point as helium I. [中文](#)

Liquid helium at 1°K. can be solidified under an external pressure of 25 atmospheres. At higher temperatures, greater pressures are required to produce the solid. The properties of liquid helium I are such as would be expected of an ordinary liquid of very low boiling point. It is far otherwise with liquid helium II. In the first place, it is an immediate inference from the phase diagram that liquid helium II under its own vapour pressure remains liquid at absolute zero, for even in the neighbourhood of 1°K. the boundary line between the solid and liquid phases tends to become parallel with the temperature axis at a pressure of approximately 25 atmospheres. Since dp/dt (the slope of the boundary line) approaches zero as the temperature is lowered, and since the volume change, Δv , is not zero, it follows from Clapeyron's equation $dp/dt = \Delta s/\Delta v$, that Δs , the change in entropy on passing from liquid to solid, also approaches zero. There can thus exist the paradoxical situation of a liquid with zero entropy. On this account the possibility has been considered by several investigators that condensed helium at absolute zero has a space-ordered structure, and that the λ -point is of the nature of an order-disorder transformation. [中文](#)

An experimental investigation of this point has been carried out by Keesom and Taconis. They examined the reflection of X-rays in a column of liquid helium II at about 1.6°K., as well as in helium above

the λ -point. No essential difference between the reflections in the two cases could be observed. Confirmation of the space-ordered theory, therefore, is still lacking, although it should be borne in mind that at 1.6°K. an appreciable degree of disorder would in any event be expected. [中文](#)

We may mention here that F. London, in a very interesting letter to *Nature*, has recalled a prediction by Einstein that a perfect Bose gas at sufficiently low temperatures should show a discontinuity in the temperature derivative of the specific heat. Applying Einstein's formula to liquid helium, London shows that the discontinuity would occur at 3.09°K. Although Einstein's discontinuity is only in the temperature derivative of the specific heat, not in the specific heat itself, London suggests that there may be some connexion with the λ -point of liquid helium. The advantage of such a theory of the λ -point is that it appears not to necessitate a space-ordered structure for the liquid at low temperatures. [中文](#)

Transport Effects

Flow Phenomena. Experiments designed to measure the viscosity of liquid helium II have led to the most surprising and apparently contradictory results. The first attempt in this direction was made at Toronto by Burton and Misener, who measured the damping of an oscillating cylinder immersed in the liquid. The value for the viscosity was found to drop suddenly at the λ -point from approximately 10^{-4} C.G.S. units for helium I to 10^{-5} C.G.S. units for helium II. Recent and more precise measurements by the similar method of an oscillating disk, made by MacWood at Leyden, give values varying from 3×10^{-5} C.G.S. units for helium II just below the λ -point to 2×10^{-6} C.G.S. units at 1.1°K. Liquid helium II thus appears to be very much less effective in damping the motion of a body immersed in it than helium gas at room temperature. [中文](#)

Attempts to measure the viscosity of helium II by measuring the rate of flow through a tube were first made by Kapitza* and by Allen and Misener in the Royal Society Mond Laboratory at Cambridge. On account of the anticipated low viscosity, the latter used very narrow tubes to lessen the rate of flow, with the extraordinary result that the rate of flow was far in excess of what would occur in a liquid of viscosity 10^{-5} C.G.S. units. Moreover, the velocity of flow did not vary linearly with the pressure head. Kapitza found a velocity proportional to the square root of the pressure head, and interpreted this as evidence that the flow was turbulent. He gave a value of 10^{-9} C.G.S. units as an upper limit to the viscosity of helium II. Giaque in California has also observed the flow of helium II through an annular tube and has obtained a temperature variation of viscosity of from 10^{-6} to 10^{-8} C.G.S. units. Allen and Misener endeavoured to reduce the velocity of flow by using finer capillaries to obtain more nearly the condition for stream-line flow, and found that the rate of flow varied as a power of the pressure head of even less than one half. It was found that the dependence of velocity on the pressure head decreased with decreasing capillary size. For glass capillaries of 0.0015 cm. radius, it was found that the velocity varied as the $1/6$ power of the pressure, whilst for capillaries of 5×10^{-5} cm. in radius, obtained by packing a metal tube with parallel wires and then drawing the tube through dies, the velocity became absolutely independent of the driving pressure. In the latter case, the velocity increased very rapidly with decreasing temperature and reached a value of 20 cm. per second at 1.1°K. The flow also appears to be non-classical in the case of the variation of length of the capillary, since a variation of length by a factor of 70 produced only a fourfold change in the velocity. 中文

On the other hand, experiments made by Burton in Toronto showed that with relatively wide and short tubes and rapid flow, the velocity is linearly proportional to the pressure head, and that the viscosity so determined agrees with the value obtained by the damping of

oscillating disks. The anomalous features appear, therefore, when the flow takes place through very long and fine capillaries (radii less than 10^{-3} cm.). [中文](#)

A little light is thrown on these curious results by the experiments of Mendelssohn and Daunt on the creep of liquid helium II in the form of mobile films over solid surfaces. If an open vessel be partially immersed in liquid helium II, it was observed that liquid gradually collected in the vessel until the liquid levels in vessel and bath were coincident. The rate of filling increased rapidly with lowering temperature. The mechanism was found to consist not in evaporation and recondensation, but in the transfer of liquid by means of surface films. At all temperatures in helium II the rate of transfer of liquid by means of the surface films was found to be independent of the difference in level. Both the thickness and the velocity of propagation of a film have been measured. The thickness is of order 5×10^{-6} cm. and the velocity increases from zero at the λ -point to 20 cm. per second at 1°K. , which gives a rate of transfer of about 10^{-4} cubic centimeters per second per centimeter width of film. If films are formed above the λ -point, that is, by helium I, they are not more than 10^{-7} cm. thick. [中文](#)

A rough synthesis of the experimental results on flow of helium II can be attempted as follows. In flow through a tube, two distinct but by no means separate processes are taking place: (a) the normal flow of a fluid with a viscosity (of order 10^{-4} C.G.S. units) which increases with decreasing temperature, and (b) creep along the inside walls of the tube by means of a surface film (of thickness of the order of 5×10^{-6} cm.), the velocity of which increases rapidly with decreasing temperature. For wide tubes, effect (a) predominates and the flow approximates to that of a normal viscous fluid. As the size of the capillary decreases, effect (b) becomes more pronounced, whilst for capillaries less than 10^{-4} cm. in radius, effect (a) becomes negligible

and the quantity of liquid flowing per second is directly proportional to the circumference of the capillary. [中文](#)

Heat Conduction. The first experiments in the transport of heat through liquid helium II were made by Rollin and Keesom; their observations showed that helium II was a most efficient agent for the transport of heat, being far more effective than copper at the same temperature. It was observed later by Allen, Peierls and Uddin, and shown more convincingly by Keesom and Saris, that the rate of heat transport was not proportional to the temperature gradient. It is thus impossible to measure a true thermal conductivity for the liquid. The rate of heat transport is greater the smaller the gradient, and reaches a value corresponding to a conductivity several thousand times as great as that of copper at room temperature with gradients of the order of 10^{-5} of a degree per cm. For a given gradient the “conductivity” increases rapidly below the λ -point to a maximum at 2.0°K. and then falls again. Simon and Pickard of Oxford have found that the anomalously high conductivity disappears at the temperature at which the specific heat becomes normal. [中文](#)

Fountain Effect. The fountain effect, which was discovered in the Mond Laboratory, shows in the most striking manner the fundamental difference between helium II and any other known liquid. In its simplest form, the effect may be described as follows. A tube is partly immersed in helium II; the lower end of the tube is a capillary; both ends are open and an arrangement is made to heat the liquid in the upper part. A steady flow of heat is thereby maintained down the capillary. Under these conditions, it is observed that the liquid inside the tube rises above the level outside, showing the existence of a pressure in the reverse direction to the heat flow. A more spectacular demonstration can be given by placing powder in the lower half of the immersed tube through which the heat flows. To produce the heat current in this case, it is sufficient to shine light on the powder. With

this arrangement the liquid may be made to rise right out of the tube, and in fact a steady “fountain” several centimeters in height can easily be produced. [中文](#)

Quantitative measurements on the magnitude of the reaction pressure are very incomplete. Some data, however, are available from measurements on the reaction to heat flowing in helium II through a tube filled with powder particles. The reaction pressure was found to attain a maximum value of approximately half an atmosphere for a gradient of 1° per cm. at 1.7°K . The value of the heat conductivity through the powder-filled tube was lower by a factor of a hundred than that through a smooth capillary of the same open cross-section. It seems, therefore, that the very large conductivity observed for helium II when the heat flows through smooth tubes is caused by violent convection currents which are set up by the reaction mechanism. This might be the reason for the apparent variation of conductivity with temperature gradient. [中文](#)

A complete understanding of the fountain effect must naturally await a satisfactory theory of the constitution of liquid helium II. However, a few interesting deductions can be made. In the first place, in the simple arrangement described above, the force holding the liquid above the bath level can only come from some form of interaction of the liquid with the walls of the tube or the attached heating wire. No other support is available, and the vapour pressure above the bath and inside the tube are sensibly the same. Secondly, this interaction must result in a downward thrust on the tube equal to the weight of liquid above the bath level. From the atomic point of view, this means that the interacting atoms are steadily transferring momentum in a downward direction to the tube, just as the thrust on the walls of a vessel containing gas implies that the atoms steadily lose momentum to the walls as they are reflected. This has the interesting consequence that the main heat transport in helium II at these temperatures (below

2.19°K.) cannot be due to the propagation of elastic waves as in ordinary liquids and solids, since elastic waves do not carry momentum. [中文](#)

Many and varied hypotheses have been made concerning the constitution of helium II. Michels, Bijl and de Boer and the present authors independently suggested that certain atoms which have more than the average energy in helium II have, as well, a larger than average mean free path inside the liquid, and that heat flow represents a drift of these moving or “excited” atoms. Later, this idea of energetic particles moving through the unexcited or “condensed” atoms was developed by Tisza to include a theory of flow. This theory has not yet reached a quantitative stage, but has proved interesting and suggestive. [中文](#)

Note added in proof: Since this article was written, F. London has published (*Phys. Rev.*, 54, 947; 1938) an enlargement of the theory which he based on the consideration that helium at low temperatures exhibited Bose–Einstein condensation phenomena. His theoretical interpretation of the behaviour of liquid helium II appears to be quite in accordance with the experimental deductions given above, particularly with regard to the properties of flow of both heat and liquid. [中文](#)

(143, 227-230; 1939)

J. F. Allen: Royal Society Mond Laboratory.

H. Jones: Imperial College, London.

* Actually Kapitza used the essentially similar method of radial flow between two parallel plates with small separation.

† To be published shortly by J. F. Allen and A. D. Misener.

‡ *Proc. Cam. Phil. Soc.* (in the Press).

液氦

艾伦·琼斯

20世纪30年代末的轰动事件之一，就是发现了液氦II（普通液氦冷却到2.19 K以下出现的一种形式的液氦）的奇特性质。20世纪30年代初，欧内斯特·卢瑟福在剑桥卡文迪什实验室建立了英国皇家学会蒙德实验室，他希望彼得·卡皮查教授能留在这个实验室工作。不过，到1939年这篇文章问世时，卡皮查已经携带蒙德实验室中的很多电磁学设备返回了莫斯科。本文所描述的液氦的一个显著的特性是，液氦在转化为氦II时黏度会迅速下降。目前利用量子力学解释氦II的这种独特性质，即液体的整体是以“玻色-爱因斯坦凝聚”形态存在——从本质上讲，就是液体作为一个整体在移动。 [英文](#)

液氦的性质最好可以从以下两个方面来考虑：（a）热平衡性质，（b）输运效应。经过莱顿和其他实验室大量仔细的研究，平衡性质已得到充分证实，其中包括不同温度下比热的确定、不同恒压下密度随温度变化的关系、以及饱和蒸气压与绝对温标的关系。而有关输运效应的研究尚处在初级阶段，诸如液体在管中的流动、热导率及相关效应等，人们对于这些现象还没有一个清晰的认识。在七月国际制冷学大会之后的一次会议，以及在英国科协的剑桥会议上，人们对液氦的输运效应进行了讨论。本文中，我们将主要讨论这个新发现的有趣的输运效应，并介绍一些目前看来结果已获得公认的最新实验。 [英文](#)

液氦的平衡性质

常压下，氦在温度为4.22 K时液化；临界温度为5.2 K。一般来说，能观测液氦性质的温度下限仅能达到1 K，因为这是用降低液面蒸气压的方法所能顺利实现的最低温度。在温度为2.19 K以及自身蒸气压下，

液氢发生了显著的转变。当液氢被冷却至温度为2.19 K时，比热从0.4 Cal/(g·K)突跃到5 Cal/(g·K)以上，之后以近于 T^5 快速下降。最近，西蒙曾指出，在通过铁钨绝热退磁产生的极低温度（0.02 K ~ 0.05 K）下，液氢的比热随 T^3 变化。 [英文](#)

温度为2.19 K时的这一转变对液氢的膨胀系数也有明显的影响。在该温度以上，膨胀系数为正，而在该温度以下则为负，但液氢的密度本身在温度为2.19 K时并没有出现不连续性。 [英文](#)

类似液氢在温度为2.19 K时发生相变的情况在物理学其他分支中也遇到过；如，在居里点的铁磁转变、某些合金的有序-无序转变、以及金属超导态与正常态的转变。液氢的相变温度被称为 λ 点，这是埃伦费斯特给它命的名。通常将低于 λ 点的液氢相称为氦II，高于 λ 点的称为氦I。 [英文](#)

在温度为1 K下，外加25个大气压可使液氢固化。在较高温度时，则需要加更大的外压来使其固化。液氦I的性质正如预期所料，即与具有极低沸点的普通液体一样，而液氦II的性质则大不相同。首先，从相图上可以直接推断出，处于自身蒸汽压下的液氦II在绝对零度时仍保持液态，因为大约25个大气压时，甚至在1 K附近，固相与液相的边界线与温度轴趋于平行。由于温度降低时边界线的斜率 dp/dt 趋近于零，而体积的变化量 Δv 不是零，利用克拉珀龙方程 $dp/dt = \Delta s/\Delta v$ 可以得到，其从液相到固相的熵变 Δs 也趋近于零。因此，可能存在一种具有零熵的奇怪液体。由于这个原因，很多研究者认为，可能凝聚态氦在绝对零度时具有空间有序结构，而 λ 点则是一种有序 - 无序转变的本质体现。 [英文](#)

凯索姆和塔康尼斯已对这点做了实验研究。他们考察了温度约为1.6 K时一段液氦II液柱和高于 λ 点时一段液氦I液柱的X射线反射。然而并没有观测到这两种情况的反射有什么本质不同。因此，关于空间有序理论的确证仍然不足，不过应该清楚的是，在温度1.6 K时，应该预期到总会有可观的无序度出现。 [英文](#)

本文中我们可以提一下，伦敦在致《自然》的一封有趣的信中回忆到，爱因斯坦曾做过一个预言，即理想玻色气体在温度足够低时，其比热对温度的导数应该是不连续的。伦敦将爱因斯坦给出的公式应用于液

氮，推断出这个不连续点应该出现在3.09 K。尽管爱因斯坦提出的不连续性只是关于比热对温度的导数而非比热本身，伦敦还是认为这与液氮的 λ 点可能会有某种关联。这样一种 λ 点理论的优势在于，在低温下似乎并不要求液氮必须具有空间有序结构。

[英文](#)

输运效应

流动现象。为测定液氮II黏度而设计的实验得到了令人非常惊讶且明显矛盾的结果。多伦多大学的伯顿和麦色纳在这个研究方向上最先进行了尝试，他们测定了浸在液氮中的振动圆筒的阻尼。研究发现，黏度值在 λ 点突然下降，从氮I的大约 10^{-4} 单位（厘米克秒制）迅速变到氮II的 10^{-5} 单位（厘米克秒制）。最近，麦克伍德在莱顿用类似的方法用振动盘进行了更精确的测量，得到的结果是氮II的黏度值从稍低于 λ 点时的 3×10^{-5} 单位（厘米克秒制）变到了1.1 K时的 2×10^{-6} 单位（厘米克秒制）。由此看来，在阻止浸入其中的物体的运动方面，液氮II的能力比室温下的氮气还要差很多。

[英文](#)

卡皮查*和英国剑桥皇家学会蒙德实验室的艾伦与麦色纳率先进行了另一种尝试，通过测量氮II流经管子的速率来测定其黏度。由于预先考虑到氮II的低黏度，后者使用了非常细的管子以降低流速。实验结果非常出人意料，氮II的流速大大超过了黏度为 10^{-5} 单位（厘米克秒制）的液体应有的流速。此外，流速并不随着压位差的变化而线性变化。卡皮查发现，流速正比于压位差的平方根，他认为这是湍流的证据。他给出了氮II黏度的上限数值为 10^{-9} 单位（厘米克秒制）。加利福尼亚的吉奥克观测了氮II通过环形管的流动，得到黏度随温度变化的范围是从 10^{-6} 单位到 10^{-8} 单位（厘米克秒制）。艾伦和麦色纳使用更细的毛细管来尽量降低氮II的流速，使之更接近于流线流的条件，研究发现流速随着压位差的不到 $1/2$ 次幂而变化。而且，毛细管越细，速度对于压位差的依赖性越小。对于半径为0.0015厘米的玻璃毛细管来说，速度随压力的 $1/6$ 次幂变化，而在使用半径为 5×10^{-5} 厘米的毛细管（用平行金属丝将一根金属管子填充，再用一系列拉丝模把管子拉出，即可制得）时，速度变得与驱动压完全无关了。在后一种情况下，速度随着温度降低而非常迅速地增加，并在温度为1.1 K时达到20厘米/秒。流速随毛细管长度的变化也表现为非经典的，因为长度变化了70倍，而速度只变化了4

倍。 [英文](#)

另一方面，多伦多大学的伯顿所进行的实验指出，在使用相对粗而短的管子和更快的流速时，速度正比于压位差，并且由此确定的黏度值与通过振动盘阻尼方法得到的数值是一致的。由此看来，当氦II流经很长且很细的毛细管（半径小于 10^{-3} 厘米）时，才会出现反常特性。

[英文](#)

门德尔松和当特进行了液氦II以流动膜形式沿固体表面爬行的实验，这为理解上述异常的结果带来了一线希望。如果将一端开口的空容器的底部部分地浸入液氦II之中，就可以观察到液体沿着容器壁逐渐流于容器中，直到容器内外液面持平。液体流进容器的速度随着温度降低而迅速加快。目前已经知道，这一行为的机制并非蒸发与再凝结，而是液体以表面膜的形式迁移。研究还发现，在任何温度下，氦II以表面膜形式迁移的速度都与液面高度差无关。现在已经测定了膜的厚度与其传播速度。厚度约为 5×10^{-6} 厘米的数量级，而传播速度则由 λ 点的静止不动，增大到1K时的20厘米/秒，从而给出每厘米膜宽度的迁移速率大约为 10^{-4} 立方厘米/秒。如果膜是在 λ 点以上形成的，即由氦I形成，那么其厚度不会超过 10^{-7} 厘米。 [英文](#)

下面试着对关于氦II流动的实验结果做一大致的综述。在液氦流经管子的过程中，有两个截然不同却不可分割的过程在发生†：（a）流体的正常流，黏度（为 10^{-4} 单位（厘米克秒制）的数量级）随温度降低而增加；（b）流体以表面膜（其厚度为 5×10^{-6} 厘米的数量级）方式沿着管内壁爬行，流体的流动速度随着温度降低而快速增大。对于粗管子来说，以（a）效应为主，流动近似为普通黏性流体的流动。随着毛细管尺寸减小，（b）效应变得越来越显著，对于半径小于 10^{-4} 厘米的毛细管来说，效应（a）变得可以忽略，流动速度随着温度降低而增大，而每秒液体的流量与毛细管的周长成正比。 [英文](#)

热传导。罗林和凯索姆最早进行了液氦II的热输运实验；他们的实验观测表明，氦II是一种极为高效的热输运介质，比同温度下的铜还要高效很多。后来艾伦、佩尔斯和乌丁观测到，且经凯索姆和萨里斯令人信服地证明，热输运速率并不与温度梯度成比例。因此，不可能测得液

体的真实热导率。热传递速率越大，温度梯度就越小且这个热传递速率相当于室温下，当温度梯度为 10^{-5} 厘米数量级时铜的热导率的几千倍。对于给定的温度梯度，“热导率”在 λ 点以下快速增大，在温度为2.0 K时达到最大值，此后再次减小。牛津大学的西蒙和皮卡德发现，反常高热导率出现在比热变为正常时的温度下。 [英文](#)

喷泉效应。蒙德实验室发现了液氦II的喷泉效应，这一效应以非常惊人的方式表明了液氦II与其他任何一种已知液体的根本差别。这种喷泉效应最简单的形式可以描述如下：将一根管子部分浸入氦II中；管的下端为毛细管；两端都是开口的，并用一种装置给上半部分中的液体加热。由此保持着沿毛细管向下的热稳流。在此条件下，可以观测到管内液体上升到高于外部液面的位置，这表明在热流的相反方向存在着某种压力。关于喷泉效应更精彩的演示是，将一些粉末置于浸入管的下半部分，即有热流动的那一段。在这种条件下，为产生热流，只要将光照射于粉末之上就可以了。通过上述操作可以使液体直接上升到管口外，实际上很容易产生几厘米高的稳定“喷泉”。 [英文](#)

对于反作用压力大小的定量测量还很不完善。不过，通过测定~~氦II~~经过装满粉末颗粒的管子的热流的反作用力，已经得到一些数据。发现反作用压力，在温度为1.7 K、温度梯度为每厘米1 K时反作用压力达到最大值，约为大气压的一半。与流经具有相同开口横截面的光滑毛细管相比，氦II流经装满粉末的管子的热导率数值要低一百倍。由此看来，热流经光滑管时，人们所观测到的氦II具有的极高热导率，是由反作用机制引起强烈对流所造成的。这可能就是热导率随温度梯度明显变化的原因。 [英文](#)

当然，要完全理解喷泉效应，有待于一个令人满意的液氦II组成理论的出现。不过，现在已经可以对此作出一些有趣的推论。首先，在上面所描述的简单装置中，使管内液体保持在外部液池液面之上的力，只能来自于某种形式的相互作用，要么是液体与管壁之间，要么是液体与附着的加热导线之间。除此再没有其他支撑的可能，而且管内与液池上方的蒸气压也明显是相等的。其次，这种相互作用必然会在管壁上产生一个向下的推力，其大小等于高于液池液面之上的液体的重量。从原子层面来看，这意味着，参与相互作用的原子在向下的方向上向管壁稳定

地传递着动量，就像盛有气体的容器器壁上所受的推力，即意味着原子在被反弹的过程中稳定地向器壁转移着动量。由此得到的有趣的结论是，在这些温度（低于2.19 K）下，液氦II中的主要热输运不是像在普通液体或固体中那样归结为弹性波的传播，因为弹性波并不携带动量。

英文

关于氦II的组合，目前已提出了各式各样的假说。米歇尔斯、比尔、德布尔以及本文作者各自独立地提出，氦II中某些具有高于平均能量的原子，在液体中也具有较大的平均自由程，而热流则体现了这些运动的或“受激发的”原子的漂移。后来，这一具有活力的粒子在未激发的或“凝聚的”原子中运动的观点被蒂萨发展，并包含了流动理论。该理论尚未达到定量的程度，但已被证明是引人关注和有启发性的。

英文

附加说明：自本文写就以后，伦敦考虑了氦在低温下出现玻色 - 爱因斯坦凝聚现象而发表了一篇文章对这一理论作了进一步的扩充（《物理学评论》，第54卷，第947页；1938年）。他对于液氦II行为的理论解释，尤其是关于热和液体的流动性质，似乎与上面所给出的实验推论颇为吻合。

英文

（王耀杨 翻译；陶宏杰 审稿）

* 实际上，卡皮查使用一种本质上类似的方法，即两个近距离平行盘之间的径向流。

† 艾伦和麦色纳将要发表的文章。

‡ 《剑桥哲学学会会刊》（正在印刷中）。

Disintegration of Uranium by Neutrons: a New Type of Nuclear Reaction

L. Meitner and O. R. Frisch

This is the first record in *Nature* referring to the stimulated disintegration of uranium nuclei by neutrons. Lise Meitner, an Austrian, had worked in Berlin with Otto Hahn until she was expelled in 1938 because of the German government's policy on people of Jewish origin. Otto Frisch, then working at Niels Bohr's institute in Copenhagen, was Meitner's nephew. The fission of uranium nuclei is of course the basis on which the first nuclear weapons were constructed. 中

文

ON bombarding uranium with neutrons, Fermi and collaborators¹ found that at least four radioactive substances were produced, two of which atomic numbers larger than 92 were ascribed. Further investigations² demonstrated the existence of at least nine radioactive periods, six of which were assigned to elements beyond uranium, and nuclear isomerism had to be assumed in order to account for their chemical behaviour together with their genetic relations. 中文

In making chemical assignments, it was always assumed that these radioactive bodies had atomic numbers near that of the element bombarded, since only particles with one or two charges were known to be emitted from nuclei. A body, for example, with similar

properties to those of osmium was assumed to be eka-osmium ($Z = 94$) rather than osmium ($Z = 76$) or ruthenium ($Z = 44$). 中文

Following up an observation of Curie and Savitch³, Hahn and Strassmann⁴ found that a group of at least three radioactive bodies, formed from uranium under neutron bombardment, were chemically similar to barium and, therefore, presumably isotopic with radium. Further investigation⁵, however, showed that it was impossible to separate these bodies from barium (although mesothorium, an isotope of radium, was readily separated in the same experiment), so that Hahn and Strassmann were forced to conclude that *isotopes of barium ($Z = 56$) are formed as a consequence of the bombardment of uranium ($Z = 92$) with neutrons.* 中文

At first sight, this result seems very hard to understand. The formation of elements much below uranium has been considered before, but was always rejected for physical reasons, so long as the chemical evidence was not entirely clear cut. The emission, within a short time, of a large number of charged particles may be regarded as excluded by the small penetrability of the “Coulomb barrier”, indicated by Gamov’s theory of alpha decay. 中文

On the basis, however, of present ideas about the behaviour of heavy nuclei⁶, an entirely different and essentially classical picture of these new disintegration processes suggests itself. On account of their close packing and strong energy exchange, the particles in a heavy nucleus would be expected to move in a collective way which has some resemblance to the movement of a liquid drop. If the movement is made sufficiently violent by adding energy, such a drop may divide itself into two smaller drops. 中文

In the discussion of the energies involved in the deformation of nuclei, the concept of surface tension of nuclear matter has been used⁷ and its value has been estimated from simple considerations regarding

nuclear forces. It must be remembered, however, that the surface tension of a charged droplet is diminished by its charge, and a rough estimate shows that the surface tension of nuclei, decreasing with increasing nuclear charge, may become zero for atomic numbers of the order of 100. [中文](#)

It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size (the precise ratio of sizes depending on finer structural features and perhaps partly on chance). These two nuclei will repel each other and should gain a total kinetic energy of c. 200 Mev., as calculated from nuclear radius and charge. This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system. The whole “fission” process can thus be described in an essentially classical way, without having to consider quantum-mechanical “tunnel effects”, which would actually be extremely small, on account of the large masses involved. [中文](#)

After division, the high neutron/proton ratio of uranium will tend to readjust itself by beta decay to the lower value suitable for lighter elements. Probably each part will thus give rise to a chain of disintegrations. If one of the parts is an isotope of barium⁵, the other will be krypton ($Z = 92-56$), which might decay through rubidium, strontium and yttrium to zirconium. Perhaps one or two of the supposed barium-lanthanum-cerium chains are then actually strontium-yttrium-zirconium chains. [中文](#)

It is possible⁵, and seems to us rather probable, that the periods which have been ascribed to elements beyond uranium are also due to light elements. From the chemical evidence, the two short periods (10 sec. and 40 sec.) so far ascribed to ²³⁹U might be masurium isotopes ($Z = 43$) decaying through ruthenium, rhodium, palladium and silver into cadmium. [中文](#)

In all these cases it might not be necessary to assume nuclear isomerism; but the different radioactive periods belonging to the same chemical element may then be attributed to different isotopes of this element, since varying proportions of neutrons may be given to the two parts of the uranium nucleus. 中文

By bombarding thorium with neutrons, activities are obtained which have been ascribed to radium and actinium isotopes⁸. Some of these periods are approximately equal to periods of barium and lanthanum isotopes⁵ resulting from the bombardment of uranium. We should therefore like to suggest that these periods are due to a “fission” of thorium which is like that of uranium and results partly in the same products. Of course, it would be especially interesting if one could obtain one of these products from a light element, for example, by means of neutron capture. 中文

It might be mentioned that the body with half-life 24 min.² which was chemically identified with uranium is probably really ^{239}U , and goes over into an eka-rhenium which appears inactive but may decay slowly, probably with emission of alpha particles. (From inspection of the natural radioactive elements, ^{239}U cannot be expected to give more than one or two beta decays; the long chain of observed decays has always puzzled us.) The formation of this body is a typical resonance process⁹; the compound state must have a life-time a million times longer than the time it would take the nucleus to divide itself. Perhaps this state corresponds to some highly symmetrical type of motion of nuclear matter which does not favour “fission” of the nucleus. 中文

(143, 239-240; 1939)

Lise Meitner: Physical Institute, Academy of Sciences, Stockholm.

O. R. Frisch: Institute of Theoretical Physics, University, Copenhagen, Jan. 16.

References:

1. Fermi. E., Amaldi, F., d' Agostino, O., Rasetti, F., and Segrè, E. *Proc. Roy. Soc., A*, **146**, 483 (1934).
2. See Meitner, L., Hahn, O., and Strassmann, F., *Z. Phys.*, **106**, 249 (1937).
3. Curie, I., and Savitch, P., *C.R.*, **206**, 906, 1643 (1938).
4. Hahn, O., and Strassmann, F., *Naturwiss.*, **26**, 756 (1938).
5. Hahn, O., and Strassmann, F., *Naturwiss.*, **27**, 11 (1939).
6. Bohr, N., *Nature*, **137**, 344, 351 (1936).
7. Bohr, N., and Kalckar, F., *Kgl. Danske Vid. Selskab, Math. Phys. Medd.*, **14**, Nr. 10 (1937).
8. See Meitner, L., Strassmann, F., and Hahn, O., *Z. Phys.*, **109**, 538 (1938).
9. Bethe, A. H., and Placzek, G., *Phys. Rev.*, **51**, 450 (1937).

由中子引起的铀衰变：一类新型核反应

迈特纳，弗里施

这是《自然》中最早谈及铀核受中子激发而产生衰变的文章。奥地利学者莉泽·迈特纳曾在柏林与奥托·哈恩一起工作至1938年，后因德国政府的反犹政策而被驱逐。奥托·弗里施是迈特纳的侄子，当时在哥本哈根的尼尔斯·玻尔的研究机构中工作。当然，最早的核武器就是基于铀核裂变制造而成的。 [英文](#)

费米及其合作者发现^[1]，用中子轰击铀核以后，至少会产生出四种放射性物质，其中两种放射性物质的原子序数均大于92。通过进一步的研究^[2]表明，事实上至少存在九种放射周期，其中有六种属于铀后面的元素，为了解释它们的化学行为及其衍生关系，必须假定存在核同质异能性。 [英文](#)

人们在进行化学研究时，经常会假定这些放射性物质的原子序数与被轰击元素的原子序数相近，因为据目前所知，核受轰击后只会发射出带一个或两个电荷的粒子。例如，轰击铀核得到的类似于钷的化学性质的物质，被假定为类钷（ $Z = 94$ ）而不是钷（ $Z = 76$ ）或者钷（ $Z = 44$ ）。 [英文](#)

沿着居里和萨维奇^[3]的观测结果继续探究下去，哈恩和施特拉斯曼^[4]发现，中子轰击铀核时至少能形成三种放射性物质，它们的化学性质与钡类似，因而推测其为镭的同位素。然而进一步的研究显示^[5]，这些放射性物质几乎不能与钡分离（然而在相同的实验中，新钷——一种镭的同位素——很容易与钡分离），因此哈恩和施特拉斯曼被迫得出这样的结论：用中子轰击铀（ $Z = 92$ ）核的结果是产生了钡（ $Z = 56$ ）的同

位素。 [英文](#)

乍看起来，这个实验结果似乎让人很难理解。因为人们以前轰击铀核时，也曾考虑过存在比铀原子序数小很多的元素形成，但是在化学证据尚未完全明晰之前，这种想法总是因为一些物理原因而被排除。伽莫夫的 α 衰变理论指出，由于穿透“库仑势垒”的可能性极小，所以在短时间内要发射出大量带电微粒是不可能的。 [英文](#)

不过，以目前关于重核^[6]行为的观点为基础，对于这种新型核衰变过程，我们想到了一种完全不同、本质上又很经典的假设。它的大致内容如下：由于紧密堆积和强烈的能量交换，预期重核中的微粒会以整体方式运动，有些类似于液滴的运动。如果外加的能量能使这种运动变得足够剧烈，这个“液滴”就可能会分裂为两个较小的部分。 [英文](#)

在讨论核变形过程中所涉及的能量问题时，需要用到核物质表面张力的概念^[7]，但人们只是在考虑核力存在的前提下估算过其数值。不过必须记住，带电微滴的表面张力因其所带的电荷而减小，并且核的表面张力随着核电荷的增加而减小，粗略的估计显示，当原子序数达到100时核的表面张力可能会减为零。 [英文](#)

由此看来，铀核也许只具有较小的稳定性，因为其在俘获中子后可能会分裂为大小基本相同的两个核（两部分大小的精确比例取决于精细结构的特征，可能还有一部分偶然因素）。这两个核将彼此排斥，根据核半径与电荷进行计算，这两个核应该会获得约为200兆电子伏的总动能。似乎可以预期，这一能量值实际上可以利用铀与周期表中部元素的敛集率的差别计算得到。由于涉及的物质质量较大，所以相应的量子力学中的“隧道效应”产生的影响小到可以忽略不计，因此整个“裂变”过程可以使用经典的方式来描述。 [英文](#)

具有高中子质子比的铀核分裂成两个新核以后，倾向于再进行 β 衰变，以使其调整到适合于较轻元素的较小比值。每个新核都可能会引起一条衰变反应链。如果其中一部分是钍^[5]的同位素，另外一部分就将是氡（ $Z=92-56$ ）的同位素，氡可以经由钋、铋和铊衰变链一直衰变到铅。也许有一条或两条衰变链，我们假定其可能会发生钍 - 镭 - 铀衰变，而实际上发生的却是铋 - 钋 - 铊衰变。 [英文](#)

有可能^[5]，并且在我们看来非常有可能的是，那些曾被归结为铀以后元素的放射周期也是轻元素的。根据化学证据，到目前为止被归结为铀-239的两个短的放射周期（12秒和40秒）可能来源于钷的同位素（ $Z = 43$ ），其经钷、铈、铈和银衰变链衰变到钷。 [英文](#)

在上述所有情况中，都不必假定存在核同质异能性；至于属于相同元素的不同放射周期则可以归因于该元素具有不同的同位素，因为铀核分裂形成的两部分可以获得各种不同比例的中子。 [英文](#)

用中子轰击钍元素，得到了曾被认为是镭和钍的同位素所具有的放射性^[8]。其中某些元素的放射周期与轰击铀产生的钡和镭的同位素^[5]具有的放射周期是近似相等的。因此，我们倾向于认为，上述放射周期应来源于钍的“裂变”，它类似于铀的裂变过程，并在一定程度上得到了相同的产物。当然，要是能从一种轻元素得到上述产物之一（例如，通过中子俘获的方式），那就更有趣了。 [英文](#)

还要提一下，在化学上与铀相同且半衰期为24分钟^[2]的那种元素，很可能就是真正的铀-239，它进而衰变为类镭。虽然类镭似乎没有放射性，但也可能是在缓慢地衰变，并有可能伴随着 α 粒子的发射。（根据对天然放射性元素已有的认识，铀-239不可能发生超过一次或两次的 β 衰变；我们始终对观测到的衰变长链感到困惑。）这种物质的形成是典型的共振过程^[9]；复合态所具有的寿命一定比核分裂所需要的时间长一百万倍。也许这种状态适合于某些不会发生“裂变”的核物质的高度对称性的运动方式。 [英文](#)

（王耀杨 翻译；鲍重光 审稿）

Theory of Mesons and Nuclear Forces

C. Møller and L. Rosenfeld

Mesons were so-called because they are intermediate in mass between the electron and the proton. In 1935, in a Japanese journal, Hideki Yukawa and colleagues proposed that mesons could account for the strong forces between nucleons (protons and neutrons) much as photons account for the electrical forces between charged particles of all kinds. This article by Rosenfeld and Møller, both protégés of Niels Bohr at Copenhagen, suggests how physical considerations require particular forms of the mathematical expressions (called wave functions) that agree better with experiments on the decay of light elements emitting β -particles. This prediction proved correct. [中文](#)

AS was first pointed out by Yukawa, it is in principle possible to account for the short-range forces between nuclear particles by the assumption of virtual emission and absorption processes involving intermediary particles of integral spin, the so-called *mesons*¹, the mass of which is determined by the range of the forces. As has been shown by Kemmer², the simplest wave-equations for the mesons which satisfy, besides the claim of relativistic invariance, the condition of giving a positive definite expression for the energy, reduce to four types, characterized by different co-variance properties of the wave-functions, and each allowing the existence of neutral as well as

positively and negatively charged mesons. Starting from such wave-equations, including the interaction of the meson field with the heavy nuclear constituents, the estimation of the resulting expressions for the nuclear forces has hitherto been carried out by using the ordinary perturbation method of quantum theory, and taking into consideration only the first non-vanishing approximation, in spite of the well-known lack of convergence of the method. It would thus seem desirable to discuss more closely the reliability of such results, and for this purpose a possible method of attack is suggested by an analogous situation in quantum electrodynamics, where a suitable canonical transformation allows us to separate, from the expression of the total energy of a system consisting of electrons and an electromagnetic field, a term depending only on the coordinates of the electrons and representing the Coulomb potential energy. [中文](#)

A similar method³ is, actually, applicable to a system consisting of nuclear particles and a meson field. For such a system it is, in fact, possible to find canonical transformations effecting the separation of a “static” interaction between the nuclear particles, defined as the part of the interaction which is obtained when one neglects the time-variations of the variables characterizing the positions, spins and proton or neutron states of the heavy particles. This static interaction is in all cases exactly the same as that obtained as a first approximation in the perturbation method, and there exists a lower limit, smaller but unfortunately not much smaller, than the range of the nuclear forces, to the mutual distances between two heavy particles for which the static interaction is more important than the additional non-static contributions arising from the terms, in the transformed Hamiltonian, which describe the remaining interactions between the heavy particles and the meson field. [中文](#)

Although no improvement can, of course, be obtained in this way as regards the self-energy difficulties, it would seem that consistent

results can be derived from the transformed Hamiltonian by considering only the last-mentioned interactions as a perturbation and applying a method of treatment analogous to the correspondence methods used in electrodynamics. It is especially to be noted that if, following Yukawa, we also introduce an interaction between the meson field and electrons and neutrinos, the transformed Hamiltonian contains a term which represents a direct interaction between the heavy particles and the electrons and neutrinos, and which, when treated as a small perturbation, immediately gives the probabilities of β -disintegration processes. It is perhaps to be regarded as a satisfactory feature of the point of view just outlined that, contrary to previous treatments, where the nuclear forces came out in the same stage of the perturbation method as the probabilities of β -decay, account is here taken at the outset of at least the static part of the nuclear forces. 中文

As regards the form of these static interactions, it is well known that the type of potential resulting from the four-vector meson field generally considered hitherto has the defect of including a term of dipole interaction energy which is so strongly singular for infinitely small mutual distances of the nuclear particles that it would not in general allow the existence of stationary states for a system of such particles. In order to remedy this defect, it seems necessary² to introduce besides the four-vector wave-function a further pseudoscalar wave-function for the meson field which has the property of giving rise to a static interaction of a form just capable of cancelling the dipole interaction term without affecting the others. The consideration of such a pseudoscalar meson field would also seem to be useful from the point of view of the theory of β -decay. While, for example, the four-vector theory yields⁴ exactly the same form of the β -spectrum as Fermi's original theory, the introduction of a pseudoscalar wave-function in addition to the four-vector one gives rise to a modification of the energy distribution of the β -rays which seems to open a new

possibility of a better adaptation to the experimental results.

[中文](#)

A detailed account of our work will appear shortly in the *Proceedings of the Copenhagen Academy*. [中文](#)

(143, 241-242; 1939)

C. Møller and L. Rosenfeld: Institute for Theoretical Physics, Copenhagen, Jan. 6.

References:

1. See Bhabha, *Nature* (in the Press).
2. Kemmer, *Proc. Roy. Soc., A*, **166**, 127 (1938); *Proc. Camb. Phil. Soc.*, **34**, 354 (1938).
3. Independently of our work, essentially the same method has been proposed by Stückelberg (*Phys.Rev.*, **54**, 889; 1938), to whom we are very thankful for the kind communication of his manuscript.
4. Yukawa, Sakata, Kobayasi, Taketani, *Proc. Phys. Math. Soc. Japan*, **20**, 720 (1938).

介子和核力理论

默勒，罗森菲尔德

介子因其质量介于电子和质子之间而得名。1935年，汤川秀树及其合作者在一本日本杂志中指出，介子可以用来解释核子（质子和中子）间的强力，这与光子可以用来解释所有带电粒子之间的电力类似。哥本哈根的尼尔斯·玻尔的两位高徒——罗森菲尔德和默勒在这篇文章中阐述了怎样用能与轻元素衰变放射出 β 粒子的实验吻合得更好的特定数学表达式（或称波函数）来满足物理学研究的需要。这个预言后来被证明是正确的。 [英文](#)

正如汤川秀树最先指出的，如果假设核子在虚拟的发射和吸收过程中包括具有整数自旋的媒介粒子，即所谓的“介子”^[1]，其质量取决于作用力的范围，那么原则上就可对核子之间的短程作用力作出解释。凯默^[2]的研究表明：可以把最简单的介子波动方程——既满足相对论所要求的不变性，又能给出一个正定的能量表达式——归纳为四种类型，以波函数协变性的不同进行区分，并且每一种类型都允许中性、带正电或带负电的介子存在。从这些包含介子场与重核子之间相互作用的波动方程出发，人们只能通过采用通常的量子力学微扰理论（仅考虑一阶不为零的近似值）来估算核力的最终表达式，尽管这种方法具有众所周知的非收敛性。因此对该结果的可靠性进行进一步的讨论就显得十分必要，为此有人提出也许可以参照量子电动力学对类似情况的处理方法，即用一个适当的正则变换使我们可从由若干电子和一个电磁场组成的系统的总能量表达式中将只与电子坐标有关的项与库仑势能项分开。 [英文](#)

其实，同样的方法^[3]也适用于核子和介子场组成的体系。对于这样的一个体系，实际上有可能找到一些正则变换使核子之间的“静态”相互作用被分离出来，其中静态相互作用指的是相互作用中忽略了表征重粒

子位置、自旋以及质子或中子状态的一些变量随时间变化的部分。这种静态相互作用在任何情况下都与微扰理论中的一级近似完全一致，而且，对于两个相距足以使静态相互作用远大于非静态相互作用项的重粒子，它们之间的距离存在一个下限，然而不幸的是，这个下限与核力力程相比虽小但没有小很多。所谓非静态相互作用项，指的是在变换后的哈密顿量中那些用来描述重粒子与介子场之间剩余作用的项。 [英文](#)

尽管这种方法并没有解决自能的困难，但是我们在仅考虑最后提到的剩余相互作用项作为微扰并应用与电动力学中类似的处理方法时，可以从变换的哈密顿量中得到自洽的结果。特别值得注意的是，如果按照汤川秀树的理论，我们也在介子场、电子和中微子之间引入一种相互作用，则变换后的哈密顿量就含有描述重粒子和电子及中微子之间直接作用的一项，当我们把它视为小微扰的时候，就可以立即给出发生 β 衰变的概率。对于上述理论来说，一开始就考虑了核力中的静态作用部分，这或许可以被认为是一个令人满意的构想，但这与以前的处理方法相反，之前核力是与 β 衰变概率在微扰法中的同一步中出现。 [英文](#)

迄今为止，人们普遍认为，这些静态相互作用的形式来自四矢量介子场的这种类型的势存在一个缺陷，就是包含一个偶极相互作用能项，当核子之间的距离趋于无穷小时，它如此奇异以至于在一般情况下不能允许这种粒子的系统存在定态。为了弥补这个缺陷，看来除了四矢量波函数以外，还有必要^[2]把一个赝标量波函数引入介子场，这个波函数的作用是引出一个静态相互作用，其作用刚好能够抵消偶极相互作用项而又不影响其他项。从 β 衰变理论的角度来看，考虑这种赝标量介子场似乎也是有意义的。举例来说，由四矢量理论得到^[4]的 β 光谱与早先费米理论中的 β 光谱形式完全相同，把赝标量波函数叠加到四矢量波函数上后， β 射线的能量分布将被修正，这为与实验结果更好地吻合提供了新的可能。 [英文](#)

我们的详细工作报告很快将发表在《哥本哈根学会学报》上。

[英文](#)

（胡雪兰 翻译；厉光烈 审稿）

Surface Transport in Liquid Helium II

J. G. Daunt and K. Mendelssohn

Experimenters had recently discovered some strange behaviours in liquid helium—in particular, its seeming ability to flow with no viscosity. Here physicists John Daunt and Kurt Mendelssohn of the Clarendon Laboratory in Oxford report a further odd effect. They had placed a container, open at the top and holding liquid helium, into a bath of the same liquid. Applying heat inside the vessel, they had found that a thin film of liquid flowed up and over the vessel's lip, linking the two otherwise separate fluids. The authors suggest that the phenomenon may be linked to the recently noted “fountain effect”, in which the heat from a weak light beam can expel a jet of liquid helium from a container. 中

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IN our previous communications¹ on the “transfer” of liquid helium II by a surface film above the liquid level, we stressed the similarity of this “transfer” with the so-called transport phenomena in the free liquid, and suggested that the latter might be due to a process similar to the transfer above the liquid level. Later experiments on the formation of this film² seemed further to strengthen the conception that there existed a similar surface transport below the liquid level, and we have recently made two observations which seem to corroborate this hypothesis:

(a) A small Dewar vessel (see Fig. 1) containing a heating coil was suspended by a thread in a bath of liquid helium II. When no heat was supplied, the levels of the liquid both inside and outside the vessel adjusted themselves to the same height L_1 , owing to the “transfer” through the film on the interconnecting glass surface. When, however, a current was passed through the heating coil, the level of the liquid inside the vessel *rose* above the outside level and took up an equilibrium position L_2 . By increasing the connecting surface between the vessel and bath by a number of wires, differences between inside and outside levels up to 5 mm. could be obtained. This clearly shows that there exists a “transfer” of helium from a colder to a hotter place when a temperature gradient is imposed. On further increasing the heat supplied, however, the evaporation from the vessel became the predominant factor and the inside level fell below that of the bath.

中文

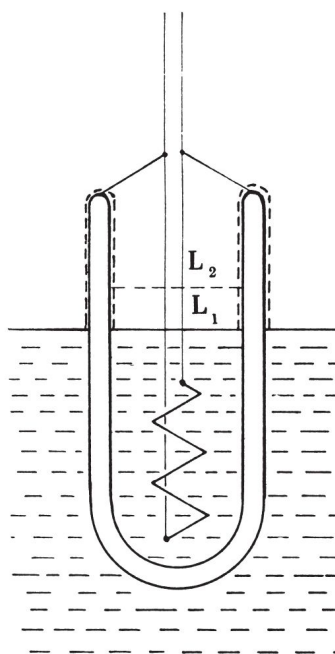
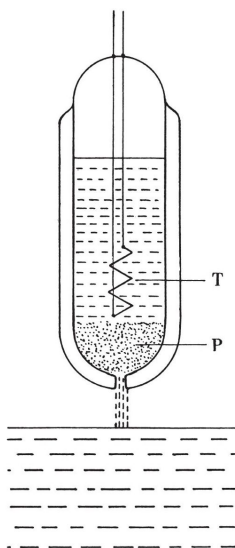


Fig. 1 中文

This effect is quite analogous to the “fountain phenomenon” in the bulk liquid, discovered by Allen and Jones³. However, in the present

case the transfer of liquid must be carried out through the surface film above the liquid level, which shows that there exists a flow of helium against a temperature gradient, even if the two containers are not connected by free liquid. One may conclude therefore that the “fountain phenomenon” in the bulk liquid is probably also due to a surface transfer, though in this case along the surface below the liquid level. This hypothesis is further strengthened by the fact that the “fountain phenomenon” is more pronounced when tubes containing fine powder are used to connect the two volumes of liquid rather than a straight capillary, for which the available surface is comparatively small⁴. 中文

(b) A Dewar vessel (see Fig. 2) was closed at the top and had a hole at the lower end which was constricted by a plug, P , of fine emery powder. It contained a phosphor-bronze thermometer, T , and was suspended in a bath of liquid helium II. When the Dewar vessel was lifted out of the bath, the liquid ran rapidly out of the vessel through P and fell into the bath, and at the same time the temperature of the inside liquid was noticed to rise by about 0.01° . On lowering the vessel so that now liquid ran from the bath into the vessel, the liquid inside was cooled by a similar amount. 中文



This mechano-caloric effect is evidently the reverse of the “fountain phenomenon”, for whereas the latter means that the setting up of a temperature difference results in a flow of liquid helium II, the mechano-caloric effect shows that a flow of liquid helium II is accompanied by a development of heat (or cold). Such a caloric effect has actually been postulated by Tisza⁵ for a flow of liquid helium II through capillaries. It seems to us, however, that the anomalous phenomena of liquid helium II are not so much caused by capillary flow as by a transport along solid surfaces; and these results seem to indicate that the heat content of those atoms transported by surface flow must be lower than average. The hypothesis that the transport phenomena in the bulk liquid are due (at least primarily) to a surface transport similar to the “transfer” above the liquid level seems also to agree with observations by Allen and Misener⁶ and H. London⁷, as well as with theoretical considerations of F. London⁸. 中文

A more detailed discussion of this tentative explanation with regard to these and other results will be given elsewhere. 中文

(143, 719-720; 1939)

J. G. Daunt and K. Mendelssohn: Clarendon Laboratory, Oxford, March 21.

References:

1. Daunt and Mendelssohn, *Nature*, **141**, 911; and **142**, 475 (1938) and *Proc. Roy. Soc.*, in the Press.
2. To be published shortly.
3. Allen and Jones, *Nature*, **141**, 243 (1938).
4. Allen and Reekie, *Proc. Camb. Phil. Soc.*, **35**, 114 (1939).
5. Tisza, *Nature*, **141**, 913 (1938); *C.R.*, **207**, 1186 (1938).
6. Allen and Misener, *Nature*, **142**, 643 (1938); see also Allen and Jones, *Nature*, **143**, 227 (1939).
7. London, H., *Nature*, **142**, 612 (1938).
8. London, F., *Phys. Rev.*, **54**, 947 (1938).

液氦II中的表面传输

当特，门德尔松

最近的实验研究发现了液氦的一些奇特的行为，特别是它似乎具有完全无黏滞流动的能力。而在这篇文章中，牛津克拉伦登实验室的物理学家约翰·当特和库尔特·门德尔松报道了一个更为古怪的效应。他们将一个盛有液氦的上端开口的容器放置于液氦池中。在容器内加热时，他们发现有一薄层液膜向上流动，越过容器的边缘将两部分分开的液体连接在一起。本文作者认为这个现象可能与当时刚刚为人所知的“喷泉效应”有关，在“喷泉效应”中，微弱的光束产生的热量就可以使液氦从容器中喷射而出。 [英文](#)

之前关于液氦II通过液面上的表面膜进行“迁移”的讨论中^[1]，我们强调这种“迁移”与所谓自由液体中的传输现象非常相似，并指出后者可能是由一个类似于在液面上迁移的过程引起的。后来关于表面膜形成的一些实验^[2]似乎进一步证实了这种说法，即在液面下存在着类似的表面传输，而且我们最近做的两项观察实验似乎也证实了这一假设：

(a) 用一根线系着一个装有加热线圈的小杜瓦瓶（如图1）浸没在液氦II中。当不加热的时候，杜瓦瓶内外的液面通过自我调节达到相同的高度 L_1 ，这是由于液氦II以膜的形式在相互连接的玻璃表面“迁移”造成的。然而，当给加热线圈通以电流的时候，杜瓦瓶内的液面会上升到高于瓶外的液面并稳定在高度 L_2 。如果用一些金属丝来增加杜瓦瓶与池中液氦的接触面积，瓶内外的液面高度差就可以上升到5毫米。这清楚地表明，当存在温度差的时候，氦会从温度较低的地方“迁移”到温度较高的地方。然而，当进一步加热时，瓶内的蒸发就成为主导因素，因此，杜瓦瓶内的液面会下降到低于池中的液面高度。 [英文](#)

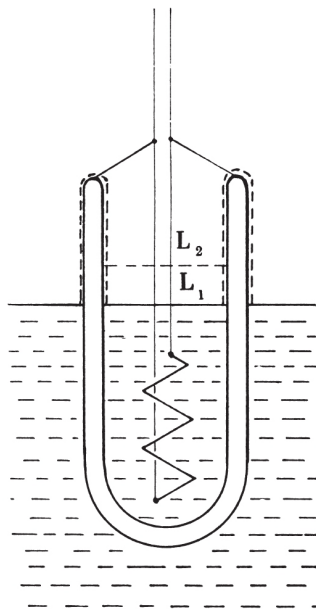


图1 英文

这一效应与艾伦和琼斯^[3]在体相液体中发现的“喷泉现象”极为相似。然而，在我们的实验中，液体迁移必须通过液面上的表面膜才能实现，这说明：即使两个容器之间没有自由液体相连通，也会存在与温度梯度方向相反的液氮流。有人也许因此得出结论：瓶内液体中的“喷泉现象”可能也是由于表面迁移而产生的，尽管在这种情况下迁移处于液面之下。下面的事实则进一步证实了这一假设：当用装有细粉的管子连接两个容器中的液体时，产生的“喷泉现象”比用直毛细管时更加明显，因为毛细管可进行迁移的表面积相对较小^[4]。 英文

(b) 一个顶部封闭的杜瓦瓶（如图2）底部有一个洞，洞口上方是由细金刚砂粉形成的填塞物 P 。瓶中还有一个由磷青铜制成的温度计 T ，它被悬挂在液氮II池中。当杜瓦瓶被升高到液氮II池面以上时，瓶内的液体很快地通过 P 流入液氮II池中，同时，瓶内液体的温度升高约0.01度。当降低杜瓦瓶使液体得以从液氮II池流入瓶中的时候，瓶内液体的温度也降低了大体相同的度数。 英文

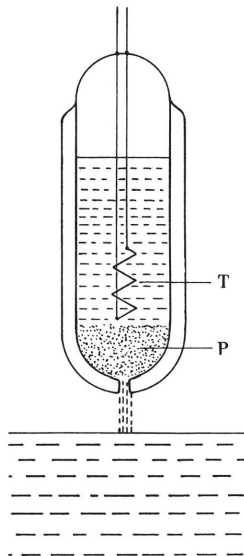


图2 英文

这一机械-热效应显然与“喷泉现象”正好相反，因为后者说明温度差导致了液氦II流的形成，而机械-热效应则显示液氦II流的形成伴随着温度的变化。实际上，蒂萨^[5]根据通过毛细管的液氦II流曾提出过关于这一热效应的假设。不过，在我们看来，与其说液氦II流的异常现象是由毛细管流引起的，不如说是由固体表面传输造成的；这些结果似乎表明，那些在表面传输的原子的热容肯定低于平均值。体相液体中的传输现象是（至少主要是）由一种类似于液面上的“迁移”的表面传输而引起的，这一假设似乎与艾伦和麦色纳^[6]以及伦敦^[7]的观察结果相一致，同时也与伦敦^[8]的理论研究相吻合。 英文

有关上述以及其他一些研究成果的尝试性解释，我们将在别处进行更为详细的讨论。 英文

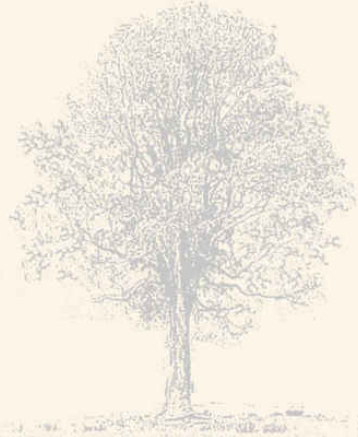
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图书在版编目 (CIP) 数据

《自然》百年物理经典. II : 英汉对照 / (英) 菲利普·鲍尔 (Philip Ball) , 赵忠贤主编. --北京 : 外语教学与研究出版社 , 2020.9

(《自然》学科经典系列)

ISBN 978-7-5213-1946-0

I . ①自... II . ①菲... ②赵... III . ①物理学 - 文集 - 英、汉 IV .
①O4-53

中国版本图书馆CIP数据核字 (2020) 第126023号

出 版 人 徐建忠

项目统筹 章思英

项目负责 刘晓楠 王丽霞

责任编辑 王丽霞

责任校对 黄小斌

封面设计 孙莉明 高 蕾

版式设计 孙莉明

出版发行 外语教学与研究出版社

社 址 北京市西三环北路19号 (100089)

网 址 <http://www.fltrp.com>

印 刷 北京华联印刷有限公司

开 本 787×1092 1/16

印 张 56.5

版 次 2020年8月第1版 2020年8月第1次印刷

书 号 ISBN 978-7-5213-1946-0

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目录

1939

Physical Evidence for the Division of Heavy Nuclei under Neutron Bombardment

中子轰击导致重核分裂的物理证据

The Fundamental Length Introduced by the Theory of the Mesotron (Meson)

介子理论中的基本长度

Energy Obtained by Transmutation

嬗变产生的能量

Cause, Purpose and Economy of Natural Laws: Minimum Principles in Physics

自然规律的起源、宗旨和经济性：物理学的极小原理

The “Failure” of Quantum Theory at Short Ranges and High Energies

短程和高能中量子理论的“失败”

Liberation of Neutrons in the Nuclear Explosion of Uranium

铀核爆炸时中子的释放

Products of the Fission of the Uranium Nucleus

铀核的裂变产物

New Products of the Fission of the Thorium Nucleus

钍核裂变的新产物

Number of Neutrons Liberated in the Nuclear Fission of Uranium

铀核裂变时释放的中子数量

Control of the Chain Reaction Involved in Fission of the Uranium Nucleus

铀核裂变中链式反应的控制

Emission of Neutrons Accompanying the Fission of Uranium Nuclei

伴随铀核裂变的中子发射

Fission of Heavy Nuclei: a New Type of Nuclear Disintegration

重核裂变：一种新型的核蜕变

Energy of Neutrons Liberated in the Nuclear Fission of Uranium
Induced by Thermal Neutrons

在热中子诱发的铀核裂变中释放出的中子的能量

Nuclear Reactions in the Continuous Energy Region

连续能量区域的核反应

The Scattering by Uranium Nuclei of Fast Neutrons and the
Possible Neutron Emission Resulting from Fission

铀核的快中子散射与可能源于裂变的中子发射

Recent Experimental Results in Nuclear Isomerism

核同质异能性的最新实验结果

Cosmic Ray Ionization Bursts

宇宙射线的“电离暴”

Measurements of the Velocity of Light

光速的测定

The Evolution of the Stars

恒星的演化

Radioactive Gases Evolved in Uranium Fission

铀核裂变时放出的放射性气体

1940

Scattering of Mesons and the Magnetic Moments of Proton and
Neutron

介子散射与质子和中子的磁矩

Evidence for Transformation of Mesotrons into Electrons

介子向电子转化的证明

Capture Cross-sections for Thermal Neutrons in Thorium, Lead
and Uranium 238

钍、铅和铀-238中热中子的俘获截面

The Mass Centre in Relativity

相对论中的质心

The Theory of Nuclear Forces

核力的理论

Excited States of Stable Nuclei

稳定核的激发态

Considerations Concerning the Fundaments of Theoretical Physics

关于理论物理基础的思考

1945

Causality or Indeterminism?

因果律还是非决定论？

1947

Processes Involving Charged Mesons

涉及带电介子的过程

A Floating Magnet

悬浮的磁体

Observations on the Tracks of Slow Mesons in Photographic Emulsions

感光乳胶中慢介子径迹的观测

Evidence for the Existence of New Unstable Elementary Particles

新的不稳定基本粒子存在的证据

1948

A New Microscopic Principle

一种新的显微原理

1949

Observations with Electron-sensitive Plates Exposed to Cosmic Radiation

在宇宙辐射下曝光的电子敏感底片的观测

1956

Correlation between Photons in Two Coherent Beams of Light

两个相干光束中光子间的相关性

The Neutrino

中微子

1958

Production of High Temperatures and Nuclear Reactions in a Gas Discharge

气体放电中产生的高温和核反应

Co-operative Phenomena in Hot Plasmas

热等离子体中的协同现象

1960

Stimulated Optical Radiation in Ruby

红宝石中的受激光辐射

1965

Time's Arrow and Entropy

时间之箭和熵

Opening Electrical Contact: Boiling Metal or High-density Plasma?

断电接触：沸腾的金属还是高密度等离子体？

Structural Basis of Neutron and Proton Magic Numbers in Atomic Nuclei

中子和质子在原子核中的幻数的结构基础

Character Recognition by Holography

利用全息术的字符识别

A Dense Packing of Hard Spheres with Five-fold Symmetry

具有五重对称性的硬球的密堆积

Reconstruction of Phase Objects by Holography

用全息术实现的相位物体的重建

1971

Ball Lightning as an Optical Illusion

球状闪电是一种视错觉

Synchrotron Radiation as a Source for X-ray Diffraction

作为X射线衍射光源的同步辐射

Estimation of Nuclear Explosion Energies from Microbarograph Records

根据微压计记录估计出的核爆炸能量

Bomb ^{14}C in the Human Population

进入人体的核弹 ^{14}C

Statistical Mechanics and Quantum Mechanics

统计力学和量子力学

1972

The Macroscopic Level of Quantum Mechanics

宏观层次的量子力学

Computer Analyses of Gravitational Radiation Detector Coincidences

引力辐射探测器符合计数的计算机分析

1973

Image Formation by Induced Local Interactions: Examples Employing Nuclear Magnetic Resonance

诱导局域相互作用成像：核磁共振应用实例

Experiments on Polishing of Diamond

金刚石抛光实验

1974

Black Hole Explosions?

黑洞爆炸？

1989

Observation of Cold Nuclear Fusion in Condensed Matter

凝聚态物质中观察到的冷核聚变

Problems with the γ -ray Spectrum in the Fleischmann *et al.* Experiments

弗莱施曼等人实验中 γ 射线谱的问题

Upper Bounds on “Cold Fusion” in Electrolytic Cells

电解池中“冷核聚变”的上限

1990

Limits on the Emission of Neutrons, γ -rays, Electrons and Protons from Pons/Fleischmann Electrolytic Cells

庞斯/弗莱施曼电解池的中子、 γ 射线、电子和质子发射的上限

Positioning Single Atoms with a Scanning Tunnelling Microscope

用扫描隧道显微镜定位单个原子

Light-emitting Diodes Based on Conjugated Polymers

基于共轭聚合物的发光二极管

1991

Superconductivity at 18 K in Potassium-doped C₆₀

掺钾的C₆₀在18 K时的超导性

1992

Curling and Closure of Graphitic Networks under Electron-beam

Irradiation

石墨网络在电子束照射下的卷曲与闭合

1993

Superconductivity above 130 K in the Hg-Ba-Ca-Cu-O System

Hg-Ba-Ca-Cu-O体系在130 K以上时的超导性

1997

Experimental Quantum Teleportation

量子隐形传态实验

Localization of Light in a Disordered Medium

无序介质中光的局域化

1998

Extraordinary Optical Transmission through Sub-wavelength Hole Arrays

通过亚波长孔洞阵列的超常光透射现象

A Silicon-based Nuclear Spin Quantum Computer

硅基核自旋量子计算机

Collective Dynamics of “Small-world” Networks

“小世界”网络的集体动力学

An Electrophoretic Ink for All-printed Reflective Electronic Displays

一种可用于全印刷反射式电子显示器的电泳墨水

1999

Light Speed Reduction to 17 Metres per Second in an Ultracold Atomic Gas

光速在超冷原子气中降低至17米每秒

2001

Observation of Coherent Optical Information Storage in an Atomic Medium Using Halted Light Pulses

运用停止光脉冲来观测原子介质中的相干光学信息存储

Experimental Violation of a Bell's Inequality with Efficient Detection

利用高效检测来实验验证贝尔不等式的违背

Superconductivity at 39 K in Magnesium Diboride

二硼化镁在39 K时的超导性

Observation of High-energy Neutrinos Using Čerenkov Detectors
Embedded Deep in Antarctic Ice

借助南极冰下深处的切伦科夫探测器观测高能中微子

2003

Upper Limits to Submillimetre-range Forces from Extra Space-
time Dimensions

来自额外空间维度在亚毫米尺度上力程的上限

2004

A Precision Measurement of the Mass of the Top Quark
顶夸克质量的精确测量

2005

Experimental Investigation of Geologically Produced
Antineutrinos with KamLAND

KamLAND对地质来源的反中微子的实验研究

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Volume II

Physical Evidence for the Division of Heavy Nuclei under Neutron Bombardment

O. R. Frisch

Otto Hahn and Fritz Strassmann in 1938 had found convincing chemical evidence for the fission of uranium nuclei. After bombarding uranium nuclei with neutrons, they had found traces of barium nuclei, with atomic weight 56, suggesting a roughly equal splitting of the nuclei. Here Otto Frisch of the Institute of Theoretical Physics in Copenhagen gives clinching physical evidence of the process. Calculations suggested that the fission fragments should have energies of perhaps 200 million electronvolts, and so should create significant ionization in a chamber. In experiments, Frisch had detected such ionization events and, from the level of ionization, estimated the atomic weight of the fragments as about 70, not too far from 56, and certainly less than uranium's 92. [中文](#)

FROM chemical evidence, Hahn and Strassmann¹ conclude that radioactive barium nuclei (atomic number $Z = 56$) are produced when uranium ($Z = 92$) is bombarded by neutrons. It has been pointed out² that this might be explained as a result of a “fission” of the uranium nucleus, similar to the division of a droplet into two. The energy liberated in such processes was estimated to be about 200

Mev., both from mass defect considerations and from the repulsion of the two nuclei resulting from the “fission” process. 中文

If this picture is correct, one would expect fast-moving nuclei, of atomic number about 40–50 and atomic weight 100–150, and up to 100 Mev. energy, to emerge from a layer of uranium bombarded with neutrons. In spite of their high energy, these nuclei should have a range, in air, of a few millimetres only, on account of their high effective charge (estimated to be about 20), which implies very dense ionization. Each such particle should produce a total of about three million ion pairs. 中文

By means of a uranium-lined ionization chamber, connected to a linear amplifier, I have succeeded in demonstrating the occurrence of such bursts of ionization. The amplifier was connected to a thyratron which was biased so as to count only pulses corresponding to at least 5×10^5 ion pairs. About fifteen particles a minute were recorded when 300 mgm. of radium, mixed with beryllium, was placed one centimetre from the uranium lining. No pulses at all were recorded during repeated check runs of several hours total duration when either the neutron source or the uranium lining was removed. With the neutron source at a distance of four centimetres from the uranium lining, surrounding the source with paraffin wax enhanced the effect by a factor of two. 中文

It was checked that the number of pulses depended linearly on the strength of the neutron source; this was done in order to exclude the possibility that the pulses are produced by accidental summation of smaller pulses. When the amplifier was connected to an oscillograph, the large pulses could be seen very distinctly on the background of much smaller pulses due to the alpha particles of the uranium. 中文

By varying the bias of the thyratron, the maximum size of pulses was

found to correspond to at least two million ion pairs, or an energy loss of 70 Mev. of the particle within the chamber. Since the longest path of a particle in the chamber was three centimetres and the chamber was filled with hydrogen at atmospheric pressure, the particles must ionize so heavily, in spite of their energy of at least 70 Mev., that they can make two million ion pairs on a path equivalent to 0.8 cm. of air or less. From this it can be estimated that the ionizing particles must have an atomic weight of at least about seventy, assuming a reasonable connexion between atomic weight and effective charge. This seems to be conclusive physical evidence for the breaking up of uranium nuclei into parts of comparable size, as indicated by the experiments of Hahn and Strassmann. [中文](#)

Experiments with thorium instead of uranium gave quite similar results, except that surrounding the neutron source with paraffin did not enhance, but slightly diminished, the effect. This gives evidence in favour of the suggestion² that also in the case of thorium, some, if not all, of the activities produced by neutron bombardment³ should be ascribed to light elements. It should be remembered that no enhancement by paraffin has been found for the activities produced in thorium³ (except for one which is isotopic with thorium and is almost certainly produced by simple capture of the neutron). [中文](#)

Prof. Meitner has suggested another interesting experiment. If a metal plate is placed close to a uranium layer bombarded with neutrons, one would expect an active deposit of the light atoms emitted in the "fission" of the uranium to form on the plate. We hope to carry out such experiments, using the powerful source of neutrons which our high-tension apparatus will soon be able to provide. [中文](#)

(143, 276; 1939)

Otto Robert Frisch: Institute of Theoretical Physics, University, Copenhagen, Jan. 16.

References:

1. Hahn, O., and Strassmann, F., *Naturwiss.*, **27**, 11 (1939).
2. Meitner, L., and Frisch, O. R., *Nature* [**143**, 239 (1939)].
3. See Meitner, L., Strassmann, F., and Hahn, O., *Z. Phys.*, **109**, 538 (1938).

中子轰击导致重核分裂的物理证据

弗里施

1938年奥托·哈恩和弗里茨·施特拉斯曼发现了铀核裂变的可信的化学证据。他们在使用中子轰击铀核之后，发现了原子序数为56的钡原子核，这表明铀核几乎是对等地分裂为两半。这篇文章中哥本哈根理论物理研究所的奥托·弗里施给出了这个过程的明确的物理证据。计算表明裂变碎片应该具有大约200兆电子伏的能量，因此应该在电离室中产生显著的电离反应。弗里施在实验中已探测到了这种相关的电离情况，从电离的量级他估算出产生的碎片的原子序数应为70左右，与56相差不远，但明显小于铀的原子序数92。

[英文](#)

根据化学证据，哈恩和施特拉斯曼^[1]作出了当中子轰击铀（原子序数 $Z = 92$ ）时会产生放射性钡核（原子序数 $Z = 56$ ）的结论。此前我们已经指出^[2]，这种现象可以解释为铀核的“裂变”，就像一个液滴一分为二那样。无论是根据质量亏损，还是根据“裂变”过程中产生的两核之间的排斥反应，都可估算出这一铀核“裂变”过程中释放出来的能量大约为200兆电子伏。

[英文](#)

如果上述描述是正确的，那就可以预期，用中子轰击铀原子层时可以发出高速运动的原子核，其原子序数和原子量分别处于40~50和100~150的范围内，能量上达到100兆电子伏。尽管这些核的能量很高，但它们在空气中只有几毫米的射程，这是因为它们具有高的有效电荷（估计为20），而这意味着具有极为密集的电离作用，每个这样的粒子会产生总计约300万个离子对。

[英文](#)

利用一个与线性放大器连接的铀衬电离室，我成功证实了这种电离脉冲的出现。放大器与一个有偏置的闸流管相连，以便能对那些相当于

至少 5×10^5 个离子对的脉冲计数。把300毫克混有铍的镭放置在距离铀衬一厘米处时，每分钟能记录到大约15个粒子。在重复进行的长达几个小时的检验测量中，无论是移走中子源还是移走铀衬，都根本记录不到任何脉冲。而当中子源距离铀衬4厘米远时，用石蜡包裹中子源却能使效应增加一倍。 [英文](#)

现已证明脉冲数目与中子源的强度具有线性关系；这是为了排除脉冲源于偶然的较小脉冲累积而产生的可能性。当把放大器与示波器相连时，可以看到在铀发射的 α 粒子产生的非常小的脉冲背景之上有非常明显的大脉冲。 [英文](#)

通过调节闸流管的偏压，可以发现最大脉冲幅度对应于至少200万个离子对，或者说相当于粒子在电离室内损失了70兆电子伏的能量。由于粒子在电离室内的最长路径只有3厘米，并且电离室内充满了一个大气压的氢气，因此，尽管粒子具有至少70兆电子伏的能量，但它们必定会发生强烈的电离以至于在相当于0.8厘米空气的路径上产生了200万个离子对。根据这一结果，假设原子量与有效电荷之间具有合理关联的话，我们就可以估算出电离粒子的原子序数应该至少是70。这对铀核分裂成大小相当的两个部分似乎是个决定性的物理证据，正如哈恩和施特拉斯曼的实验结果所示。 [英文](#)

用钍代替铀所做的实验给出了相当类似的结果，只是用石蜡包裹中子源后效应并没有增强，反而是略有减弱。先前我们曾提出^[2]在钍的实验中用中子轰击所产生的某些（如果不是全部的话）放射性^[3]应该归属为轻元素，上述实验结果为这一观点提供了有力的证据。同时我们还应该记住，在钍产生的放射性实验^[3]中用石蜡包裹中子源后效应并没有增强（只有一次例外，那是因为使用了钍的某种同位素，并且几乎可以确定是由于单纯的中子俘获而产生的）。 [英文](#)

迈特纳教授曾提出过另外一个有趣的实验。如果将一块金属板置于用中子轰击的铀层附近，就可以预期金属板上会形成铀“裂变”过程中所发射出的轻原子的放射性沉积物。我们希望实现诸如利用高压装置便能提供更强中子源的实验。 [英文](#)

The Fundamental Length Introduced by the Theory of the Mesotron (Meson)*

H. J. Bhabha

By 1939, physicists understood that the framework in which they discussed the behaviour of particles such as electrons and protons was in some sense incomplete. There was particular concern over the particles, called mesotrons, which were intermediate in mass between electrons and protons, but which carried electrical charge. Homi J. Bhabha was an Indian graduate student at Cambridge and Bristol. He was among the first to appreciate the wider implications of mesons. In the 1960s Bhabha returned to India and became the head of the Indian Atomic Energy Commission. He was killed in an air crash in 1966. [中文](#)

IT is well known that the vector theory of the meson¹ contains a fundamental length in the interaction of mesons with protons and neutrons determined by the fact that the mass of the meson appears explicitly in the denominator of some of the interaction terms. This circumstance has the result that in those elementary processes in which the momentum change is large compared with mc , m being the mass of the meson, the interaction becomes very large, leading to Heisenberg explosions, and to greater divergences in some second-order effects than is the case in radiation theory. This has led Heitler²

and others to the view that the meson theory in its present form is quite incorrect for meson energies larger than about mc^2 , and Heisenberg³ to the position that quantum mechanics is competent to deal accurately with only those elementary processes in which the condition⁴ due to Wataghin,

$$\left| \left(\frac{E_1 - E_2}{c} \right)^2 - (\mathbf{p}_1 - \mathbf{p}_2)^2 \right| \ll \left(\frac{\hbar}{r_0} \right)^2, \quad (1)$$

is satisfied, E and p being the initial and final energy and momenta of a particle concerned in the process, and r_0 a fundamental length of the order $\hbar/mc$. The purpose of this note is to bring forward an argument which, it seems to me, shows first that the limitation of quantum mechanics by the condition (1), if true, cannot be based on the explosions as derivable from the theory of the meson, and secondly, to throw some doubt on (1) itself as a limit to the correctness of quantum mechanics. [中文](#)

The argument runs as follows. Let us consider uncharged mesons⁵ for simplicity, since this changes nothing essential to the argument, and consider the Hamiltonian given in A (49)¹. The interaction (58 a) in this contains terms which become very large when the momentum change of the meson becomes large compared to mc in a suitable Lorenz frame. These terms, which lead to explosions, are due *as much to the transverse meson waves as to the longitudinal ones*, even in the limit when the proton may be considered to be moving non-relativistically. Further, the critical momentum above which explosions begin to appear becomes lower the smaller mc , and becomes vanishingly small when $mc \rightarrow 0$. [中文](#)

On the other hand, *the exact quantized equations of motion for the meson field derivable from this Hamiltonian* (A (14) and (15), with the appropriate simplifications for a neutral meson), namely,

$$G_{\mu\nu} = -\left(\frac{\partial}{\partial \chi^\mu} U_\nu - \frac{\partial}{\partial \chi^\nu} U_\mu\right) + \frac{g_2}{\hbar c} \psi + \gamma^\mu \gamma^\nu \tau_3 \psi$$

$$\frac{\partial}{\partial \chi_\mu} b_{\mu\nu} = \frac{m^2 c^2}{\hbar^2} U_\nu + \frac{g_1}{\hbar c} \psi + \gamma^\nu \tau_3 \psi$$

go over continuously into the Maxwell equations when $m \rightarrow 0$. But one knows from electrodynamics that although there are circumstances in which the emission of a large number of quanta may be more probable than the emission of a single quantum, as in the so-called “infra-red catastrophe”, this in no way sets a limit to the accuracy of quantum mechanics *and does not interfere with the calculation of less probable processes by the methods of perturbation theory*. Moreover, it is just those processes where the emission of a large number of quanta is very probable which can be calculated classically. 中文

In view of the above circumstances, we must conclude that the appearance of the fundamental length determined by the mass of the meson in the interaction term in no way sets a limit to the accuracy of quantum mechanics. For example, in the collision of two protons with energy very large compared to mc^2 , the probability becomes large for the simultaneous emission of a large number of mesons, which is the analogue of the “infra-red catastrophe” for quanta of finite rest mass, and hence quantum mechanics is none the less competent to deal with it. It can similarly be shown that *we can calculate the production of large explosions to a high degree of accuracy by treating the meson field quantities classically*, that is, as non-quantized magnitudes, for since mesons satisfy Einstein-Bose statistics, the meson field becomes a classical one just in the case where we are dealing with a large number of mesons. 中文

Hence if a fundamental length r_0 exists which limits the applicability of present quantum mechanics to the cases satisfying (1), this length r_0 has nothing to do with the mass of the meson or the appearance of explosions. Quantum mechanics in its present form cannot be strictly valid since it leads to divergent results connected with the self-

energies of point charges; but these limitations are probably due to the fact that it is not the quantization of the correct classical equations for point charges, and not to the existence of a fundamental length r_0 . These equations have only recently been given by Dirac⁶ and their quantization has not yet appeared. 中文

Accordingly, we might expect that very fast protons (or neutrons) would produce explosions consisting of mesons of momenta roughly mc , while mesons with energy much larger than the proton rest-energy would *not* do so, and their scattering by protons would also decrease with increasing energy, in analogy with the Compton effect. 中文

It can be shown that the classical retarded meson field and potentials due to the world line of a classically moving proton or neutron can be written as the sum of two parts. The first part has exactly the form that the corresponding electromagnetic quantities would have for a point charge and point dipole (represented by a six-vector) moving along a classical world line, and does not contain the mass of the meson. The second part has no singularity at any point of space including the world line of the proton, and goes to zero as the mass of the meson $m \rightarrow 0$. The meson singularities are therefore *identical* with the electromagnetic singularities, and it is possible to eliminate these to the same degree and in the same way as has been done by Dirac⁶ for the electromagnetic field of a point charge. 中文

The detailed calculations will be published elsewhere. 中文

(143, 276-277; 1939)

H. J. Bhabha: Gonville and Caius College, Cambridge, Dec. 17.

References:

1. Kemmer, *Nature*, **141**, 116 (1938); *Proc. Roy. Soc., A*, **166**, 127 (1938). Fröhlich, Heitler and Kemmer, *Proc. Roy. Soc., A*, **166**, 154 (1938). Bhabha, *Nature*, **141**, 117 (1938); *Proc. Roy. Soc., A*, **166**, 501 (1938), referred to above as A; Yukawa, Sakata, and Taketani, *Proc. Phys. Math. Soc. Japan*, **20**, 319 (1938). Stueckelberg, *Helv. Phys. Acta*,

- 11, 299 (1938).
2. Heitler, *Proc. Roy. Soc., A*, **166** (1938).
3. Heisenberg, *Z. Phys.*, **110**, 251 (1938).
4. Wataghin, *Z. Phys.*, **66**, 650 (1931); **73**, 126 (1931).
5. Kemmer, *Proc. Camb. Phil. Soc.*, **34**, 354 (1938).
6. Dirac, *Proc. Roy. Soc., A*, **167**, 148 (1938). See also Pryce, *Proc. Roy. Soc., A*, **168**, 389 (1938).

* The name “mesotron” has been suggested by Anderson and Nedder-meyer (*Nature*, **142**, 874; 1938) for the new particle found in cosmic radiation with a mass intermediate between that of the electron and proton. It is felt that the “tr” in this word is redundant, since it does not belong to the Greek root “meso” for middle; the “tr” in neutron and electron belong, of course, to the roots “neutr” and “electra”. In these circumstances, it seems better to follow the suggestion of Bohr and to use electron to denote particles of electronic mass independently of their charge, and negaton and positon to differentiate between the sign of the charge. It would therefore be more logical and also shorter to call the new particle a meson instead of a mesotron.

介子理论中的基本长度*

巴巴

1939年，物理学家认识到，讨论电子和质子等粒子行为的理论框架在某种意义上是不够完善的，尤其是对于一种叫介子的粒子，它的质量介于电子和质子之间而且携带电荷。霍米·巴巴是剑桥大学和布里斯托尔大学的印度籍研究生。他也是第一批对介子具有的更广泛含义进行认真思考的学者之一。20世纪60年代巴巴回到印度并成为印度原子能委员会的主席。1966年他在一次空难中不幸去世。

英文

众所周知，介子矢量理论^[1]包含介子与质子和中子相互作用的基本长度，它是由介子质量出现在一些相互作用项的分母中的事实所决定的。这种情况使得在一些动量变化大于 mc （ m 为介子质量）的基本过程中相互作用变得非常大，从而导致了海森堡爆炸，同时也使一些二阶效应与辐射理论所得结果相比更加发散。这使海特勒^[2]和其他一些人注意到介子理论的现有形式因给出介子能量大于 mc^2 而是完全错误的，海森堡^[3]也指出，量子力学仅可以完美地解决那些满足瓦塔金条件^[4]的基本过程，该条件如下：

$$\left| \left(\frac{E_1 - E_2}{c} \right)^2 - (\vec{p}_1 - \vec{p}_2)^2 \right| \ll \left(\frac{\hbar}{r_0} \right)^2 \quad (1)$$

式中 E 和 p 在这个过程中分别代表一个粒子初态和终态的能量和动量， r_0 为与 $\hbar/mc$ 具有同样量级的基本长度。我这篇短文的目的是要引出一个论点，首先该论点指出量子力学的应用范围如果真的仅限于条件（1）满足的情况，那么就不可能出现介子理论所预言的爆炸现象；其次，我对条件（1）本身作为量子力学正确性的限制条件表示质疑。

英文

这个论点具体如下：为了简单起见，我们考虑不带电荷的介子^[5]的情况，因为带电情况的变化对这个论题没有本质上的影响，另外我们还用到A（49）式^[1]中给出的哈密顿量。在适当的洛伦兹框架下，当介子动量的变化大到可以和 mc 相比拟时，表示相互作用的（58a）式中的一些项就会变得非常大。即使在质子运动可能被认为是非相对论性的极限情况下，这些可引发爆炸的项也是一样由横向介子波和纵向介子波引起的。此外，爆炸开始出现时的临界动量在 mc 变小时也会变小，当 mc 趋于0时，临界动量会变得几乎为0。 [英文](#)

另一方面，由哈密顿量（A（14）和（15）），并在中性介子的假设下作适当简化）导出的严格介子场量子化运动方程，即：

$$G_{\mu\nu} = -\left(\frac{\partial}{\partial\chi^\mu}U_\nu - \frac{\partial}{\partial\chi^\nu}U_\mu\right) + \frac{g_2}{\hbar c}\psi + \gamma^\mu\gamma^\nu\tau_3\psi$$

$$\frac{\partial}{\partial\chi_\mu}b_{\mu\nu} = \frac{m^2c^2}{\hbar^2}U_\nu + \frac{g_1}{\hbar c}\psi + \gamma^\nu\tau_3\psi$$

在 m 趋于0时会连续地过渡到麦克斯韦方程。但是根据电动力学，我们知道正如所谓的“红外灾难”，虽然发射大量量子的概率要大于发射单个量子的概率，但这决不会限制量子力学的适用范围，也不会干预应用微扰理论计算小概率的过程。而且正是那些可以用经典方法计算的过程有可能发射大量量子。 [英文](#)

我们可以由此得出结论，取决于相互作用项中介子质量的基本长度绝不可能对量子力学的精确性有所限制。举例来讲，当两个能量大到足以和 mc^2 相比拟的质子发生碰撞的时候，同时发射大量介子的可能性就会变大，这类似于与具有有限静止质量的量子相关的“红外灾难”，因此量子力学仍然可以解决这类问题。同样我们可以指出，用经典方法处理介子场量能够精确地计算出大爆炸的结果，也就是说，既然介子满足爱因斯坦-玻色统计，那么当我们处理包括大量介子的问题时，对于非量子化的场量，介子场就变成了一个经典场。 [英文](#)

因此，如果基本长度 r_0 的出现使现有的量子力学理论只能应用于满足式（1）的情况，那么这个长度 r_0 就与介子质量或爆炸的出现无关。量子力学的现有形式不可能是严格正确的，因为它在涉及点电荷自能问题时会产生发散的结果；但是，这种局限性可能是由于正确的经典点电荷

方程没有量子化，而不是因为引入了基本长度 r_0 。最近只有狄拉克^[6]给出了这些方程，不过尚未得到这些方程的量子化形式。 英文

因此，我们可以预测快速运动的质子（或中子）会引发爆炸，放出动量大约为 mc 的介子，而当介子能量远大于质子的静止能量时则不可能引发爆炸，而且能量越大，质子对介子的散射越弱，这与康普顿效应类似。 英文

这表明，由经典运动的质子或中子的世界线所决定的经典的推迟介子场和势能可以写成两部分之和。第一部分的具体形式为一个点电荷和点偶极子（用一个六维矢量描述）沿经典的世界线运动所对应的电磁场量，而不包含介子质量。第二部分在包括质子世界线在内的任何空间点上都不会出现奇异点，而且当介子质量 m 趋于0时它也变为0。因此，介子的奇异点与电磁场的奇异点是一样的，可以参照狄拉克^[6]对点电荷电磁场的处理方法以同样的方式、在同一程度上消除这些奇异点。 英文

详细的计算结果将发表在其他地方。 英文

（胡雪兰 翻译；厉光烈 审稿）

* “mesotron”是安德森和尼德-迈耶（《自然》，142，874；1938）为在宇宙线中发现的新粒子所取的名字，该粒子的质量介于电子和质子之间。大家感觉“tr”在这个单词中是多余的，因为它并不属于前面表示“中间”的意思的希腊词根“meso”，而中子和电子中的“tr”是属于词根“neutr”和“electra”的，在这种情况下最好接受玻尔的建议，即用电子表示与所带电荷正负无关的带电粒子，而用负电子和正电子来区分所带电荷的正负号。因此把这种新粒子命名为“meson”比将其称为“mesotron”更符合逻辑、也更简洁。

Energy Obtained by Transmutation

This editorial comments on the possibility of deriving energy, perhaps in explosive form, from nuclear transmutation. The likelihood, it suggests, is remote. Meanwhile, recent experiments had demonstrated the artificial transmutation of most elements, including gold, though without any repercussions for world financial stability. The goal of harnessing nuclear energy seemed far off, partly because significant energy can be released only in processes involving the heaviest and rare elements. Yet the first atomic weapon was detonated only six years later, made possible by the enrichment of vast quantities of uranium with the easily fissionable isotope ^{235}U , which constitutes only 0.7% of the element naturally. [中文](#)

MR. Robert D. Potter, of "Science Service", Washington, D.C., points out that the confirmation of the artificial breakdown of uranium announced in New York (see also *Nature*, Feb. 11, p. 233) is in the direct succession of experiments carried out in recent years on the transmutation of the elements. For centuries, alchemists had dreamed of transmuting base metals into gold. It was imagined that enormous wealth would be at hand for the discoverer of this transmutation, and dire forecasts of the effects of this discovery were made, such as a complete revolution on the financial pattern of the world. We know that this transmutation has now been achieved for most of the known chemical elements. Transmutation's biggest result is the theoretical

incentive it has provided for further physical researches. In a similar way, the dream of releasing the large amounts of energy locked inside atoms has been in the minds of men for many years. When the most efficient transformation of energy takes place in the atom of uranium so that a neutron can slip into it, the energy released is only one fifteenth of that required to bring it about. In fact, neutrons are so easily absorbed by all atomic nuclei that many of the neutrons produced with such poor efficiency will only go into atoms other than uranium. There need be little fear of an explosion in Nature due to uranium. The very heavy elements, in which such an energy release can be secured, occur only in very small amounts in the Earth's crust. The release of atomic energy can only be achieved by direct experiment with this end in view and with elaborate laboratory apparatus. [中文](#)

(143, 328; 1939)

嬗变产生的能量

这篇社论就从核嬗变中获取能量（或许以爆炸的形式）的可能性进行了评论。文中提出，这种可能性还很遥远。同时，最近的实验已经证实了包括金在内的大多数元素可实现人工嬗变，而这并未对世界金融的稳定造成影响。利用核能的想法似乎遥不可及，部分原因是只有最重且稀有的那些元素的嬗变过程才能释放出巨大的能量。然而仅在六年后，通过大量天然铀富集获得的铀-235使得第一颗原子弹爆炸成功，而这种易裂变的同位素铀-235仅占天然铀元素的0.7%。

[英文](#)

华盛顿特区科学服务社的罗伯特·波特先生指出，纽约宣布的铀的人工嬗变（也见《自然》2月11日，第233页）是近年来对元素嬗变问题所进行的实验的直接延续。几个世纪以来，炼金术士都梦想将普通金属转变成金子。有人认为发现了这种嬗变，巨大的财富就会唾手可得，有人还对这个发现的结果做出了极端的预测，例如这将是一次世界金融格局的彻底变革。我们知道，现在对于大多数已知的化学元素，这类嬗变都已实现。嬗变的最大成效是，它为进一步的物理研究提供了理论发展的动力。同样，将禁锢在原子内部的大量能量释放出来，一直是人们心中多年以来的梦想。当铀原子中发生最有效的能量转化，并使一个中子进入其中时，所释放的能量仅是促使该过程发生所需能量的1/15。实际上，中子很容易被各种原子核吸收，以至于许多如此低效的中子只能进入其他原子而不能进入铀。不必过于担心自然界的铀会引起爆炸。能够确保这种能量释放得非常重的元素在地壳中的含量很少。原子能量的释放只能用直接的实验来实现，为达到这样的目的而做的实验是要在精心制作的实验装置中进行的。

[英文](#)

（沈乃澂 翻译；朱永生 审稿）

Cause, Purpose and Economy of Natural Laws*: Minimum Principles in Physics

M. Born

In the 1920s, Max Born, based at the University of Göttingen, had been one of the founders of quantum mechanics. The German government's decision that Jewish people could no longer teach at German universities made it necessary for him to leave Germany; after a brief stay at Cambridge he settled in Edinburgh where he and his family remained for several decades. Born was an exceptionally lucid lecturer. This general lecture on the laws of physics is a model of its kind. [中文](#)

WITHOUT claiming to be a classical scholar, I think that the earliest reference in literature to the problems which I wish to treat here is contained in Virgil's "Aeneid", Book I, line 369, in the words "taurino quantum possent circumdare tergo." [中文](#)

When Dido landed at the site of the citadel of Carthage, she opened negotiations with the inhabitants for some land and was offered for her money only as much as she could surround with a bull's hide. But the astute woman cut the bull's hide into narrow strips, joined them end-to-end and with this long string encompassed a considerable piece of land, the nucleus of her kingdom. To do this she had evidently to solve a mathematical question—the celebrated "problem of Dido": to

find a closed curve of given circumference having maximum area. We do not know how she solved it, by trial, by reasoning, or by intuition. In any event, the correct answer is not difficult to guess: it is the circle. But the mathematical proof of this fact has only been attained by modern mathematical methods. 中文

In saying that the first appearance of this kind of problem in literature is that quoted above I am not, of course, suggesting that problems of minima and maxima had never occurred before in the life of mankind. In fact, nearly every application of reason to a definite practical purpose is more or less an attempt to solve such a problem: to get the greatest effect from a given effort, or, putting it the other way round, to get a desired effect with the smallest effort. We see from this double formulation of the same problem that there is no essential distinction between maximum and minimum; we can speak shortly of an “extremum”, and “extremal” problems. 中文

It was during Isaac Newton’s lifetime, at the end of the seventeenth century, that geometrical and mechanical problems of extremals began to interest mathematicians, and shortly after Newton’s death (1727) the metaphysical idea of purpose or economy in Nature was linked up with them. 中文

One of the simplest examples is the optical “law of reflection” which can be expressed as a minimum principle: the beam of light from a point P_1 to another point P_2 selects just that reflecting point Q which makes the total path $P_1Q + QP_2$ as short as possible. The light behaves as if each beam had a tendency to contract, and the French philosopher, Fermat, has shown that all the laws of geometrical optics can be reduced to the same principle. Light moves like a tired messenger boy who has to reach definite destinations and carefully chooses the shortest way possible. Are we to consider this interpretation as accidental, or are we to see in it a deeper metaphysical significance? Before we can form a judgment, we must

learn more about the facts and consider other cases.

[中文](#)

The straight line is the shortest connexion between two points in space. But if we travel on our earth, we can never go exactly in a straight line since the earth's surface is not plane. The best we can do is to follow a great circle, which is the curve in which the sphere is intersected by a plane passing through the centre. The globe, however, is not an exact sphere, but is slightly flattened at the poles and bulges at the equator. What, then, about the shortest line on such a surface?

[中文](#)

Gauss hit on this problem when occupied with a geodetic triangulation of his country, the electorate of Hanover. He attacked the problem from the most general point of view and investigated the shortest lines on arbitrary surfaces. But in remembrance of his starting point he called these lines “geodesics”. They are in many ways of fundamental importance for physics.

[中文](#)

Let us consider a point P on a surface and all curves through P which have the same direction at P . It is evident that there is among them a “straightest curve”, that is, one with the smallest curvature. Hence the geodesic can be characterized by two somewhat different minimum properties: one which can be called a “local” or “differential” property, namely, to be as little curved as possible at a given point for a given direction; and the other, which can be called “total” or “integral”, namely, to be the shortest path between two points on the surface.

[中文](#)

This dualism between “local” and “total” laws appears not only in this simple geometrical problem, but also has a much wider application in physics. It lies at the root of the old controversy whether forces act directly at a distance (as assumed in Newton's theory of gravitation and the older forms of the electric and magnetic theories), or whether they act only from point to point (as in Faraday's and Maxwell's

theory of electromagnetism and all modern field theories). [中文](#)

There seems to be no objection to extremal laws of the local type; but those of the integral type make our modern mind feel uneasy: although we understand that the particle may choose at a given instant to proceed on the straightest path, we cannot see how it can quickly compare all possible motions to a distant position and choose the shortest one—this sounds altogether too metaphysical. [中文](#)

But before we follow out this line of thought, we must convince ourselves that minimum properties appear in all parts of physics, and that they are not only correct but also very useful and suggestive formulations of physical laws. [中文](#)

One field in which a minimum principle is of unquestionable utility is statics, the doctrine of the equilibrium of all kinds of systems under any forces. The centre of gravity tends to descend as far as possible; to find the configuration of stable equilibrium, one has only to look for the minimum of the height of the centre of gravity. This height, multiplied by the force of gravity, is called potential energy. [中文](#)

A chain hanging from both ends assumes a definite shape, which is determined by the condition that the height of the centre of gravity is a minimum. If the chain has very many links, we get a curve called the catenary. It can readily be shown by means of a heavy chain, the centre of gravity of which is marked by a construction of light levers, that disturbance of the equilibrium of the chain in any arbitrary way causes the centre of gravity of the chain to rise. [中文](#)

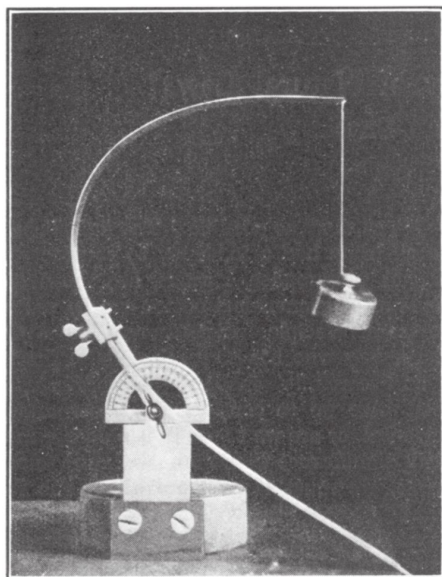


Fig. 1 中文

Fig. 1 illustrates an example where gravity competes with another force, elasticity. A steel tape is clamped at one end and carries a weight at the other. This weight is pulled downwards by gravity, while the tape tries to resist bending in virtue of its elasticity. This elastic force also has a potential energy; for a definite amount of work must be done to bend the tape into a given curved shape. Now there are definite positions of equilibrium in which the total energy, that of gravitation plus that of elasticity, is as small as possible. Generally there are two such positions. Changing the clamping angle carefully, a position is found when a jump suddenly occurs from one position to another on the opposite side. This instability is determined by the condition of minimum energy. We can summarize the facts connected with the limits of stability by drawing a graph, Fig. 2, not of the elastic lines themselves, but by plotting the angle of inclination against the distance from the free end. We obtain wave-shaped curves, all starting horizontally from the line representing the end carrying the weight. These curves have an envelope which separates the regions in which one or several curves are going through each point, and calculation shows that this envelope is just the limit of stability.

We shall return to this example later when discussing the minimum principles of dynamics. [中文](#)

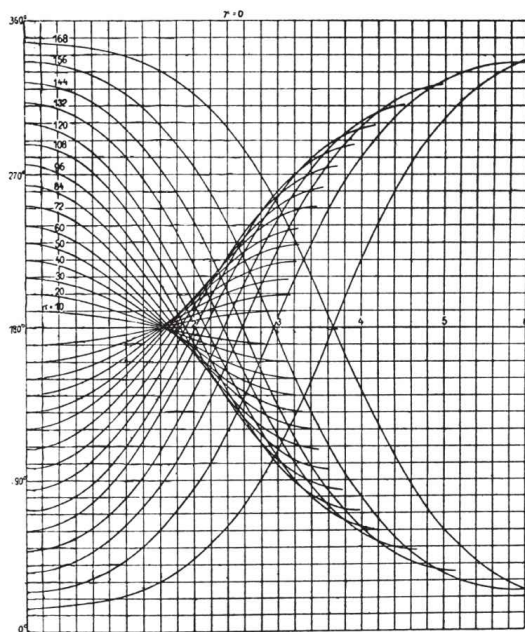


Fig. 2 [中文](#)

Another example of the statical principle of minimum energy is provided by soap bubbles. Soap films have the property of contracting as much as possible; the potential energy is proportional to the surface area. Therefore soap films are surfaces of smallest area, or minimal surfaces. Nature is an expert mathematician, quickly finding the solution. [中文](#)

These experiments are not merely pretty toys without serious background. They have been chosen only for the sake of illustration. The real importance of the principle of minimum energy can scarcely be exaggerated. All engineering constructions are based on it, and also all structural problems in physics and chemistry. [中文](#)

Models of crystal lattices provide examples of this. A crystal is a regular arrangement of atoms of definite kinds in space. Now the models representing the crystal lattices of two chemically similar

compounds, namely, common salt (NaCl) and caesium chloride (CsCl) are different in structure. Why are they different? Because, as the caesium atoms are much larger than the sodium atoms, the potential energy differs in the two cases and its minimum is attained for different configurations. 中文

Considerations of this kind, more or less quantitative, enable us to understand a great number of facts about the internal structure of solid matter. 中文

Before we proceed to the consideration of minimum principles in dynamics, where the situation is not as clear and satisfactory as in statics, we must first mention another part of physics which in a sense occupies an intermediate position between statics and dynamics. It is the theory of heat, thermodynamics and statistical mechanics. 中文

There is a very important extremum principle, discovered by Lord Kelvin, which governs irreversible processes: a quantity called “entropy” increases in the process and has a maximum for the final equilibrium state. It is not easy to describe this miraculous entropy in terms of directly observable quantities, such as volume, pressure, temperature, concentration, heat. But its meaning is immediately obvious from the point of view of atomic theory. A model will facilitate the explanation. Take a flat box like a little billiard table into which marbles can be put. If I carefully place them in the right-hand half, I have a state of partial order; if I shake the box they spread out over the whole box and attain a configuration of lower order. If I throw some marbles into the box one after the other so that their position is purely accidental, it is very improbable that they will all fall in the right-hand half. One can easily calculate the probability of a uniform distribution over the whole box as compared with one in which the majority of the marbles is in the right half; and one finds overwhelming odds in favour of the uniform distribution. Now the

statistical theory of heat interprets the entropy of a system with the aid of the probability of the distribution of the atoms, and the tendency of entropy to increase is explained by the obvious fact that states of higher disorder have a higher probability. 中文

Let us now come back to the minimum principles of dynamics. 中文

The first problem of this kind—first both in historical order and in order of simplicity—was formulated at the end of the seventeenth century by Johann Bernoulli of Basle, one of a great family which produced many famous scholars and especially mathematicians. It is the problem of the curve of quickest descent or brachistochrone: given two points at different levels, not in the same vertical line, to determine a connecting curve in such a way that the time taken by a body to slide without friction under the action of gravity from the higher point to the lower is a minimum—compared of course with all possible curves through the two points. With a model having three paths, namely, a straight line, an arc of a circle and an intermediate curve known as a cycloid, it can be shown that it is not the straight line on which a rolling ball arrives first, nor the steep descent of the circular arc, but the cycloid. If you were to try with any other curves, you would always find the same result, for the cycloid has been constructed according to the theoretical calculation. 中文

The determination of this brachistochronic property of the cycloid was a very satisfactory piece of mathematics. It attracted much attention, and there is no philosopher of this period who did not test his analytical powers by solving similar extremal problems. Another member of the Bernoulli family, Daniel Bernoulli, developed at the beginning of the eighteenth century the minimum principle of statics and applied it to the catenary and the elastics line. Encouraged by these successes, he raised the question whether it was possible to characterize the orbit, and even the motion in the orbit, of a body

subject to given forces—for example, a planet—by a minimum property of the real motion as compared with all other imagined or virtual motions. He put this question to the foremost mathematician of his time, Leonard Euler, who was very much interested in it and found, in the autumn of 1743, a solution which he explained with the help of various examples in a book published in 1744. It is the basis of the *principle of least action* which has played so prominent a part in physics right up to the present time. 中文

The history of this principle, however, is an amazing tangle of controversies, quarrels over priority and other unpleasant matters. Maupertuis, in the same year, 1744, presented a paper to the Paris Academy of Sciences in which he substituted for Fermat's optical principle of the shortest light path, which we have already discussed, a rather arbitrary hypothesis, and extended the latter, in 1746, to all kinds of motions. He never gave a satisfactory proof of his principle (which is not surprising as it is incorrect), but defended it by metaphysical arguments based on the economy of Nature. He was violently attacked by Chevalier d'Arcy in Paris, Samuel König from Bern and others, who showed that if maupertuis's principle were true, thrifty Nature would be forced in certain circumstances to spend not a minimum but a maximum of action! Euler, whose principle is quite correct, behaved rather strangely; he did not claim his own rights, but even expressed his admiration for Maupertuis's principle, which he declared to be more general. The reasons for this attitude are difficult to trace. One of them seems to have been the publication by König of a fragment of an alleged letter of Leibniz in which the principle was enunciated. The genuineness of this letter could never be proved, and it seems probable that it was a forgery designed to weaken Maupertuis's position. This may have brought Euler over to the side of Maupertuis, who was at this time president of the Berlin Academy and a special favourite of the king, Frederic II, later known as the Great. The dispute was now carried over into the sphere of the court of

Sanssouci and even into the arena of politics. Voltaire, friend of Frederic, who heartily disliked the haughty president of the Academy, took the side of the “underdog”, König, and wrote a caustic pamphlet, “Dr. Akakia”, against Maupertuis. But the king, although he thoroughly enjoyed Voltaire’s witty satire, could not sacrifice his grand president and was compelled to defend Maupertuis. This led at last to the disruption of their friendship and to Voltaire’s flight from Berlin, as described in many biographies of Frederic and of Voltaire.

中文

The curse of confusion has rested for a long period on the principle of least action. Lagrange, whose work was the culmination of the development of Newton’s dynamics, gives an unsatisfactory formulation of the principle. Jacobi restricts it in such a way that the minimum condition determines the orbit correctly; the motion in the orbit must be found with the help of the energy equation. This was an important step. But the spell was at last broken by the great Irishman, Sir William Rowan Hamilton, whose principle is mathematically absolutely correct, simple and general. At the same time, it put an end to the interpretation of the principle expressing the economy of Nature. For there is, by a kind of fortunate mathematical coincidence, a statical problem for which the statical minimum principle for the potential energy coincides formally with Hamilton’s principle of least action for the pendulum; this statical problem is the loaded steel tape considered before. The curves representing the angle of inclination of the elastic line as a function of the distance from the free end are exactly the same lines as those representing the angle of deflection of the pendulum as a function of time (see Fig. 2).

中文

Now we have seen that only those regions of the graph which are simply covered by the lines correspond to a real minimum, a stable configuration of the elastic line. There are other regions, those beyond the envelope, where two or more lines pass through a given point.

Only one of those lines corresponds to a real minimum. But both represent possible motions of the pendulum. Although the conditions at the ends of the elastic tape do not correspond exactly to those at the ends of the time interval in Hamilton's principle, there is this fact in common: if the length of the tape or the corresponding time interval in Hamilton's principle for the pendulum exceed a certain limit, there is more than one possible solution, and not each of them can correspond to a true minimum, though to a possible motion. In this way we come to the conclusion that the actual motion is not in every case distinguished by a genuine extremal property of action but by a less obvious mathematical property called "stationary" configuration.

[中文](#)

Thus the interpretation in terms of economy breaks down. We may regard the idea of finding purpose and economy in natural laws as an absurd piece of anthropomorphism, a relic of a time when metaphysical thinking dominated science. [中文](#)

The importance of Hamilton's principle lies in a different direction altogether. It is not Nature that is economical, but science. All our knowledge starts with collecting facts; but proceeds by summarizing numerous facts by simple laws and these again by more general laws. This process is very obvious in physics. We may recall, for example, Maxwell's electromagnetic theory of light, by which optics became a branch of general electrodynamics. The minimum principles are a very powerful means to this end of unification. The ideal would be to condense all laws into a single law, a universal formula, the existence of which was postulated more than a century ago by the great French astronomer, Laplace. [中文](#)

If we follow the Viennese philosopher, Ernst Mach, we must consider economy of thought as the only justification of science. I do not share this view—there are other aspects and justifications of science. But I do not deny that economy of thought and condensation of the results

are very important, and I consider Laplace's universal formula as a legitimate ideal. There is no question that the Hamiltonian principle is the adequate formulation of this tendency. It would be the universal formula if only the correct expressions for the potential energy of all forces were known. Nineteenth century thinkers believed more or less explicitly in this programme, and it was successful in an amazing degree. [中文](#)

By choosing a proper expression for the potential energy, nearly all phenomena could be described, including not only the dynamics of rigid and elastic bodies, but also that of fluids and gases, as well as electricity and magnetism, together with electronics and optics. The culmination of this development was Einstein's theory of relativity, by which the abstract principle of action regained a simple geometrical interpretation. The motions of the planets can be considered as "geodesics" in the four-dimensional space formed by adding time to our common space. Einstein's law of gravitation, which contains Newton's law as a limiting case, can also be derived from an extremum principle in which the quantity that is an extremum can be interpreted as the total curvature of the space-time world. [中文](#)

We call this period of physics which ends with the theory of relativity the classical period, in contrast to the recent period which is dominated by quantum theory. The new quantum mechanics assumes that all laws of physics are of statistical character. The fundamental quantity is a wave function which obeys laws similar to those of an acoustical or optical wave; it is not, however, an observable quantity, but determines indirectly the probability of observable processes. The point which interests us here is the fact that even this abstract wave function of quantum mechanics satisfies an extremum principle of the Hamiltonian type. [中文](#)

We are still far from knowing Laplace's universal formula, but we may be convinced that it will have the form of an extremal principle, not

because Nature has a will or purpose or economy, but because the mechanism of our thinking has no other way of condensing a complicated structure of laws into a short expression. [中文](#)

(143, 357-361; 1939)

* Substance of the Friday evening discourse delivered at the Royal Institution on February 10.

自然规律的起源、宗旨和经济性*： 物理学的极小原理

玻恩

20世纪20年代，在哥廷根大学工作的马克斯·玻恩已经是量子力学的奠基人之一了。后来，德国政府关于犹太人不能再在德国大学任教的决定使他不得不离开德国；在剑桥短暂停留后，他最终定居爱丁堡，并和其家人在那里住了几十年。玻恩是一位思路极为清晰的讲演者，这篇关于物理定律的讲演就是其中的一个典范。 [英文](#)

我并不是要表明自己是一名古典主义学者，不过我认为有关这里我要研究的问题的最早记录恐怕要追溯到维吉尔的《埃涅阿斯纪》，即第一册第369行所写的“用公牛皮围一块尽可能大的地”。 [英文](#)

当狄多来到迦太基古城时，她与当地的土著人谈判，用一定量的金币换取一头公牛的牛皮能够围起来的土地。这个精明的女人把公牛皮割成细长条并将它们首尾相连，最终圈得一片相当大的土地，这就是她王国的核心。为了做到这点，显然她得解决这样一个数学问题——著名的“狄多问题”：如何使给定周长的闭合曲线所围成的面积达到最大。我们并不知道她是如何解决这个问题的，可能用试验或推理，也可能是靠直觉。无论如何，我们不难猜到这个问题的正确答案是：一个圆。但直到现代数学方法的出现才最终从数学方面给出了证明。 [英文](#)

上面提到的内容是第一次在文字记载出现这类问题的相关记录，当然我不是指在此记录之前的人类历史中从未出现过这类求极小值和极大值的问题。实际上，每次应用推理达到某个明确实际的目标时，我们都或多或少在试图解决这样的问题：在一定的努力的基础上得到最大的效果，换句话说，即以最小的代价得到预期的效果。从以上对同一个问题

的两种表述方式中看到，求极大值与极小值的问题之间并没有本质的区别；我们可以简单地称之为“极值”或“极值函数”问题。 [英文](#)

在17世纪末的艾萨克·牛顿时代，极值函数的几何问题和力学问题开始引起数学家们的兴趣，在牛顿去世（1727年）后不久，自然界的意义或经济性等形而上学的思想逐渐与这些极值问题联系起来了。 [英文](#)

最简单的一个例子是光学中的“反射定律”，这个定律可以表述成极小原理：从某一点 P_1 传播到另一点 P_2 的光束所选择的反射点 Q 要满足总路程 $P_1Q + QP_2$ 为最短。光的行为性质表现为每束光都具有缩短路程的趋势，法国哲学家费马已经指出，几何光学的所有规律都可以归纳为这一原理。光的运动就像一个疲劳的信使，他会在到达确定的目的地之前谨慎地选择尽可能最短的路程。我们如何理解以上的解释呢？认为这是一种偶然的情况，还是我们可以从中发现更深刻的形而上学方面的意义？在我们做出判断之前，我们必须了解更多的事实，并考虑其他更多的情况。 [英文](#)

空间中两点之间最短的连线是直线。但如果我们在地球上运动时，我们永远不能精确地沿直线行进，这是因为地球的表面不是平面。而最好的选择是沿着大圆的路径，这个大圆是大圆所在的球与某一穿过球心的平面相交的曲线。然而地球并不是一个精确的球体，它的两极稍微有些扁平、赤道略微凸起。那么在这样的球面上，最短的路线是什么样子的呢？ [英文](#)

高斯利用大地三角测量方法对他所在的德国汉诺威选区进行测绘时也碰到了这个问题。他从最普遍的观点出发来处理问题，并研究了任意表面上最短的线。为了纪念他处理这个问题的出发点，他仍将这些最短的线称为“测地线”。对于物理学来说，“测地线”在许多方面都具有重要意义。 [英文](#)

我们考虑球体表面上的一点 P ，且通过 P 的所有曲线在 P 处方向相同。显然，在它们之中有一条“最直的曲线”，即曲率最小的曲线。因此，测地线可以用两种稍微不同的最小性原理来表征：第一种可被称为“局部的”或“微分的”性质，即经过某个定点并给定方向的曲线，其曲率最小；第二种被称为“整体的”或“积分的”性质，即表面上的两点之间

路程最短。 [英文](#)

“局部的”和“整体的”定律之间的二元论不仅出现在这类简单的几何问题中，而且在物理学中有着更加广泛的应用。它在早期争论物理学的基础时就已经出现，即力的作用是直接的超距作用（如牛顿引力理论和电磁理论早期形式中的假设），还是只能是点到点的作用（如法拉第和麦克斯韦的电磁学理论及所有的现代场论）。 [英文](#)

人们对局部形式的极值定律似乎并无反对意见；但以我们现在的思维来说，我们还是不太能自然地接受总体形式的极值定律：虽然我们知道粒子将在给定的瞬间沿直线行进，但是我们并不明白它是如何迅速地到达远处某个地方所有可能的路线进行对比并从中选择最短的一条的——这些听起来似乎都很形而上学。 [英文](#)

但我们在探究以上想法之前，我们自己必须深信，在物理学的所有方面都存在最小性原理，它们不仅是正确的，而且是物理定律中很有用且具有启发性的公式。 [英文](#)

毫无疑问，静力学，即各类系统在力的作用下最终都将处于平衡态的学说，成功应用了极小原理。重心趋向于处在尽量低的位置；为了得到稳定的平衡态结构，我们只能去寻求重心高度的极小值。重力乘以这个高度将得到所谓的势能。 [英文](#)

两端悬挂的一条链将呈现出确定的形状，这个形状是在重心高度取极小值的条件下得到的。如果这条链有很多链环，我们将得到被称为悬链线的曲线形状。这很容易通过一条重的链条表示出来，它的重心是用光杠杆的测量方法进行标记的，用任何方式对链条的平衡位置进行扰动都会导致链条重心的上升。 [英文](#)

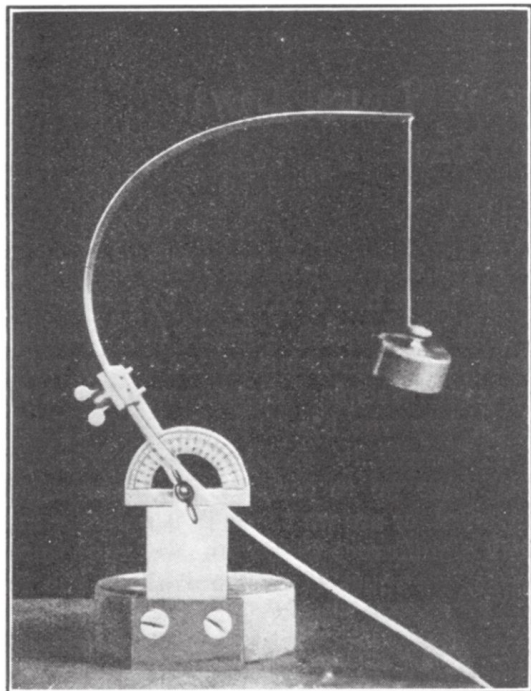


图1 英文

图1描述了一个重力与另一种力即弹力相互竞争的例子。一根钢尺一端被夹紧固定住，另一端悬挂着一个砝码。这个砝码被重力往下拉，而钢尺由于具有弹性而抵制弯曲。因为必须做一定量的功才能使钢尺弯曲成一定形状的弧线，所以弹力也有相应的势能。事实上有一些确定的平衡位置，其总的能量即引力和弹力相应的势能之和取最小值。通常存在两个这样的平衡位置。慢慢地改变钢尺被夹的角度，我们可以找到这样一个位置，该位置上的钢尺可能突然朝反方向弯曲成相反的形状。这种不稳定性是由能量极小值的条件所决定的。我们总结了与稳定性极限相关的事实并用图形（图2）表示出来，图2所画的并不是弹性曲线本身，而是倾斜角与自由端到固定点距离两者的关系曲线。我们得到了波形曲线，这些曲线都是一端挂着砝码的曲线沿水平方向的变化曲线。这些曲线具有一个包络面，它把通过同一个点的一条或几条曲线与其他曲线分隔开来，相关的计算表明，包络面就是稳定性的极限条件。后面讨论到动力学的极小原理时我们将回来继续研究这个例子。

英文

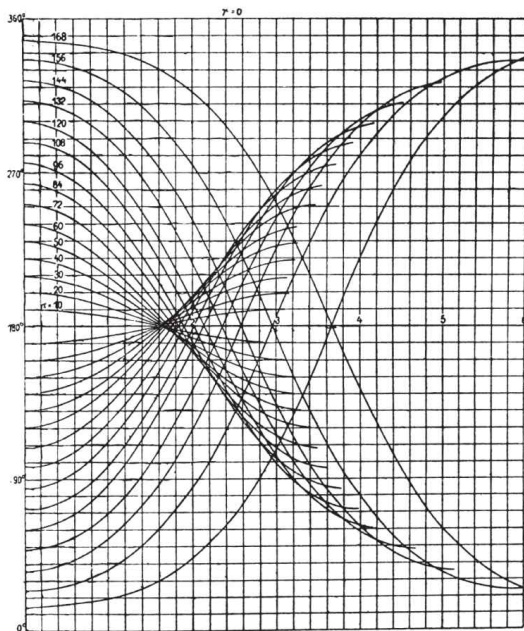


图2 英文

另一个证明极小能量静态原理的例子是肥皂泡。肥皂泡具有尽可能收缩变小的性质；其势能与表面面积成正比。因此，肥皂泡具有最小范围的表面，或者说极小的表面。自然界是一位专业的数学家，它很快就找到了这个问题的解决办法。 英文

这些实验并不是不能应用于实际的玩具模型。选择它们只是为了便于说明。我们绝对没有夸大极小能量原理的实际重要性。它是所有工程建筑的基础，也是物理学和化学中所有结构问题的基础。 英文

晶格模型提供了这类例子。晶体是确定种类的原子在空间中规则排列形成的。由两种化学性质类似的化合物即普通的盐（NaCl）和氯化铯（CsCl）各自组成的晶格的模型在结构上是不同的。为什么二者会存在这样的差别呢？因为铯原子的尺寸远大于钠原子，所以两种情况下的势能不一样，而势能取极小值时对应的原子构型也不一样。 英文

以上这类问题的考虑或多或少能从定量的角度帮助我们了解很多固体物质内部结构的情况。 英文

由于动力学中的极小原理并不像静力学中的那样清楚和令人满意，

因此，在开始考虑动力学的极小原理之前，我们有必要先提到物理学的另一部分，它在某种意义上来说是介于静力学和动力学之间的。这就是热学、热力学和统计力学的理论。 [英文](#)

开尔文勋爵发现了控制不可逆过程的很重要的极值原理：被称为“熵”的物理量在不可逆过程中是不断增大的，并在最终的平衡态下达到最大值。很难用直接的可观测量，如体积、压力、温度、浓度和热量等来描述这个不可思议的熵。但是我们可以很容易地从原子理论的角度得到熵的物理意义。以下这个模型将帮助我进一步解释熵的意义。取一个如同台球桌那样扁平的可放入弹球的盒子。如果我们小心地把这些弹球摆在盒子的右半部分，这时得到的状态是部分有序；如果我们摇动盒子使这些弹球分布在整个盒子的范围内，得到的是一个更低序的状态。如果我将这些弹球一个接一个地扔进盒子里，则每个弹球的位置都是随机的，就不太可能出现所有的弹球都落到右半部分的情况了。我们可以很容易地计算出弹球在整个盒子内均匀分布的概率，并把这个概率与大部分弹球都位于右半部分的概率进行比较；人们发现均匀分布的情况存在压倒性的优势。热学的统计理论借助原子的分布概率解释了系统中的熵，而我们可以由越无序的状态出现的概率越大这个明显的事实来解释熵增加的趋势。 [英文](#)

现在我们回来继续讨论动力学极小原理。 [英文](#)

17世纪末巴塞尔的约翰·伯努利阐述了我们要讨论的这类问题中的一个，这个问题不仅在历史顺序上是最早出现的，在这类问题中也是最简单的，伯努利家族是一个大家族，并且产生了许多著名的学者，尤其是数学家。这是一个关于最快速下降曲线或者说捷线的问题：给定两个不同水平高度上的点，它们不在同一竖直线上，为了确定这样一条曲线，使物体在重力作用下从较高点沿着该曲线无摩擦地滑到较低点的过程中时间最短，我们当然要对通过这两点的所有可能曲线进行比较。使用一个具有三条路径的模型，三条路径分别为直线、圆的一段弧线和被称为摆线的中间曲线，可以看到，最先到达较低点的并不是沿着直线滚动的小球，也不是沿着圆弧的陡峭弧度滚动的小球，而是沿着摆线滚动的小球。如果你尝试其他任何曲线，你将会发现结果总是一样的，因为摆线就是按照理论计算所得出的时间最短的轨迹。 [英文](#)

确定摆线的捷线过程在数学处理方面是完美、无可挑剔的。这类极值问题受到了广泛的关注，在那个时期，没有一个哲学家不是通过解决类似的极值问题来检验自己的分析结果的。18世纪初，伯努利家族的另一个成员丹尼尔·伯努利发展了静力学的极小原理，并成功地把该原理应用到悬链线和弹性线的情况中。在以上这些成就的鼓舞下，他提出这样一个问题：通过真实运动情况的极小性质（与其他所有想象的或可能实现的运动情况相比较），是否可以描述出给定作用力情况下物体的运动轨迹，甚至是轨迹中物体的运动情况呢？例如描述一颗行星的运动情况。他向当时最有名的数学家伦纳德·欧拉提出了这个问题，欧拉对此很感兴趣并于1743年的秋天给出了这个问题的答案，之后，他在1744年出版的书中借助各类例子对此作了进一步的解释。这就是迄今为止在物理学中一直扮演着重要角色的最小作用量原理的基础。 [英文](#)

与这个最小作用量原理有关的是一段充满混乱的不可思议的历史，其中出现了发现原理的优先权之争和其他不愉快的事件。同样是在1744年，莫佩尔蒂向巴黎科学院提交了一篇文章，文中他把我们前面已经讨论过的费马提出的最小光程的光学原理替换成一个他自己主观的假设，并于1746年把他的假设推广到所有的运动情况中。他并没有对他的原理给出满意的证明（这并不奇怪，因为他的原理本身就是不正确的），而是在自然经济性的基础上以形而上学的论据进行论证。他受到了巴黎的达西爵士、伯尔尼的塞缪尔·柯尼希和其他人的猛烈攻击，他们指出，如果莫佩尔蒂的主张是正确的话，那么一向经济节俭的自然在某些情况下将被迫做最大的而不是最小的功！欧拉提出的原理是正确的，但他的行为颇为奇怪；他非但没有声明自己发现该原理的优先权，反而对莫佩尔蒂的原理表示赞赏，并宣称这个原理是更普遍的。我们很难找到欧拉持这种态度的原因。其中的一个原因似乎是由于柯尼希公开了所谓的莱布尼茨信件的一部分，该部分对最小作用量原理也进行了阐述。这封信的真实性从未得到证实，似乎很有可能是伪造的，目的是用来削弱莫佩尔蒂的地位。这也许是使欧拉站在莫佩尔蒂这一边的原因，当时的莫佩尔蒂是柏林学院的院长并且特别受当时的国王弗雷德里克二世，也就是后来所谓的弗雷德里克大帝的喜爱。这场关于最小作用量原理的争辩不但在无忧宫的范围内容展开了，后来甚至进入了政界的活动舞台。弗雷德里克的朋友伏尔泰非常讨厌傲慢的柏林学院院长莫佩尔蒂，因此，他站到

了“受压迫者”柯尼希的一边，并写了《阿卡基亚博士》这本小册子来讽刺莫佩尔蒂。虽然弗雷德里克非常欣赏伏尔泰机智的讽刺风格，但是为了不让自己尊贵的院长的利益受到损害，他不得不替莫佩尔蒂辩护。这最终导致了弗雷德里克和伏尔泰的友谊破灭，随后伏尔泰逃离柏林，这些在许多关于弗雷德里克或伏尔泰的传记中都有所描述。 [英文](#)

如同受到了诅咒一样，人们在最小作用量原理上困惑了很长时间。拉格朗日的工作把牛顿力学发展到了极致，但是他给出的最小作用量原理的形式并不令人满意。雅可比给拉格朗日的形式加上了限制条件使得极小值条件可以给出物体正确的运动轨迹；但必须知道能量方程才能得到轨迹中具体的运动情况。这是极小原理发展历史上很重要的一步。最终，对这个原理的诅咒被伟大的爱尔兰人威廉·罗恩·哈密顿爵士打破了，他所表述的该原理在数学上是完全正确、简单且普适的。同时，他也结束了用自然的经济性来解释该原理的时代。由于幸运的数学巧合，势能的静态极小原理这个静力学问题与摆的哈密顿最小作用量原理在形式上完全符合；先前我们讨论的一端悬挂砝码的钢尺就是这种静力学情况之一。钢尺弯曲的倾斜角是其自由端到固定点距离的函数，而摆的偏转角是时间的函数，但是表示钢尺倾斜角的曲线与表示摆偏转角的曲线却是严格一致的（见图2）。 [英文](#)

现在我们已经看到，图中只有那些被曲线简单覆盖的区域对应于实际的极小值范围，即对应弹性尺形变的稳定构型。而包络面以外的其他区域中存在两条或多条曲线穿过同一个给定点的情况。其中只有一条对应实际的极小值。以上两种对应实际极小值的情况都是摆可能的运动情况。虽然弹性钢尺端点的限制条件与哈密顿原理中每个时间间隔内端点的限制条件并不严格一致，但是在以下情况中它们有一样的规律：如果钢尺的长度或相应于哈密顿原理中钟摆模型的时间间隔超过一定的极限，将不止有一种可能的解存在，虽然这些解都对应于可能的运动情况，但并不是每一个解都存在真正的极小值与之对应。在这种情况下，我们得到的结论是：实际的运动情况是否存在并不总是以真正的作用量的极值性质作为判断依据的，而是以相对不明显的数学性质即所谓的“稳态”构型作为判断依据的。 [英文](#)

因此从自然的经济性解释极小原理失败了。我们认为这种在自然规

律中寻找目的和经济性的想法是一种可笑的拟人论的想法，它是形而上学的思维主导科学的时代留下的残余。 [英文](#)

总而言之，哈密顿的极小原理的重要性体现在完全不同的方面。具有经济性的并不是自然而科学。我们所有的知识都是从收集到的事实经验出发的；但我们进一步要做的是把这些无数的事实经验总结发展成为简单的规律，并把这些简单规律再次总结发展成为更加普适的规律。在物理学中这个过程是显而易见的。我们可以回想一下，例如在麦克斯韦关于光的电磁理论中，光学变成了广义电动力学的一个分支。在达到理论大统一的过程中，极小原理是一个强有力的手段。最理想的情况是把所有的规律浓缩成一个规律，一个普适的公式，而早在一个多世纪之前，法国伟大的天文学家拉普拉斯就已经提出过这种猜想了。 [英文](#)

如果按照维也纳哲学家恩斯特·马赫的观点，则我们应该把是否具有经济性作为判断科学是否合理的唯一条件。我并不赞同这种观点——我认为还有其他判断科学合理性的方面和办法。这里我并不是认为思维的经济性和对结果的归纳不重要，而且我也认为拉普拉斯提到的普适的公式是一种合理的想法。毫无疑问，哈密顿原理是一个大家认可的倾向于成为普适规律的原理。如果已知所有作用力势能的正确表达式，哈密顿原理就将是一个普适的原理。19世纪，几乎所有的思想家们都明确相信这个原理是普适的，而这个原理也确实取得了惊人的成功。 [英文](#)

如果我们选择合适的势能表达式，哈密顿原理就可以描述几乎所有的现象，不仅包括刚体、弹性体的动力学，也包括流体、气体的动力学以及电学、磁学、电子学和光学。爱因斯坦的相对论是这个理论发展的极致，其中抽象的作用量原理又可以用简单的几何学进行解释了。在通常的空间中加入时间这个维度后，则我们可以认为行星的运动轨迹是这种四维空间中的“测地线”。牛顿运动定律作为一种极限情况被包含在爱因斯坦的引力定律当中，而我们可以从极值原理导出后者，其中，极值原理中的极值这个量可以被解释为时空世界总的曲率。 [英文](#)

我们把相对论出现之前的时期称为经典物理学的时期。与之相对的是最近以量子理论为主导的时期。新的量子力学假定所有的物理规律都具有统计特性。其中最基本的物理量是一个与声波和光波遵循类似规律

的波函数；然而，它并不是一个可观测量，而是间接决定了可观测过程的概率。这里我们感兴趣的方面是，即便是量子力学中这个抽象的波函数也是满足哈密顿形式的极值原理的。 [英文](#)

虽然要得到拉普拉斯所谓的普适公式还有很长的路要走，但我们深信最终我们将得到极值原理普适的形式，这并非出于自然界的愿望、宗旨或经济性，而是因为以我们现在的思维方式还没有其他办法能将复杂的结构规律浓缩成简单的表达式。 [英文](#)

（沈乃澍 翻译；葛墨林 审稿）

* 2月10日周五晚上玻恩在英国皇家研究院发表演说的主要内容。

The “Failure” of Quantum Theory at Short Ranges and High Energies

A. S. Eddington

Arthur Eddington was by now the most distinguished astronomer in Britain. He had turned his attention to the problems thrown up by the new quantum mechanics. He quickly replied to Bhabha's claim that quantum mechanics could not accommodate the behaviour of atomic particles at high energy with an account of how he proposed to deal theoretically with nuclei of all kinds, concluding that quantum mechanics was not in need of revision. Both Bhabha and Eddington were, unfortunately, unaware of the complications that would arise from the introduction of mesons into their developing theory. [中文](#)

IN Dr. Bhabha's letter in *Nature* of February 18, reference is made to a breakdown of quantum theory at high energies and short intervals. This seems to be widely interpreted as setting a limit to the validity of our present physical conceptions. Some indeed would associate it with a fundamental discontinuity of structure of space and time. I have no occasion to criticize Dr. Bhabha's letter which, so far as it goes, is opposed to the more extreme interpretations. But I venture to suggest that an unnecessary mystery is being made of what is really an elementary point of relativity theory. In short, we know why the

present theory has got into difficulties, and we know what must be taken into account if it is to get out of them. [中文](#)

Relativity theory begins with a denial of absolute motion. Every observed velocity dx/dt is a relative velocity of two physical objects. Likewise the “ x ” of which velocity is the time-derivative is a relative displacement of two physical objects. Both objects are connected with the space-time frame in the way pointed out by Heisenberg; namely, they are not locatable as points (or, in four dimensions, worldlines) but have an uncertainty of position and momentum. [中文](#)

Usually dx/dt and x are assigned to one of the objects (here called the object particle), the other being regarded as a reference body. In precise formulae, the reference body must evidently be a particle. The reference particle is then the physical “origin” from which the observable co-ordinate x of the object particle is measured. Current quantum theory has repeated the pre-relativity mistake of paying insufficient attention to the definition of the physical reference system to which its exact formulae are intended to apply. It enunciates formulae involving x and $\partial/\partial x$, but omits to specify the standard deviation (uncertainty) of position and momentum of the origin from which x is measured. Clearly, the formulae cannot be true for an arbitrary standard deviation; if true at all, they must hold for a particular standard deviation of position ε which ought to have been specified. Since there is no explicit reference, the actual value of ε must be implicit in the empirical constants (such as h/mc) of the quantum formulae. [中文](#)

When two object particles with co-ordinates x_1 and x_2 are considered, the displacement ξ_0 of one relative to the other is observable independently of any origin of co-ordinates, being the original observable called “ x ” in our second paragraph. This must not be confused with the co-ordinate difference $\xi = x_2 - x_1$, which introduces twice over the uncertainty of the physical origin from

which x_1 and x_2 are measured. We have (in the notation of the theory of errors)

$$\xi = \xi_0 \pm \varepsilon \sqrt{2}$$

The failure of current theory is due especially to its omission to distinguish the two observables ξ and ξ_0 . [中文](#)

The physical origin has uncertainty both of position and momentum; for if either were zero the other would be infinite, and the physical origin would not approximate to a geometrical origin with a definite world-line. An energy m_0c^2 corresponding to the mean square of the uncertain momentum is therefore associated with the origin. Except in two-body problems (in which one object particle is used as physical origin for the other) the practice is to treat all the object particles symmetrically; the physical origin must then be an additional *virtual* particle, that is, a particle inserted in the system as part of the apparatus of measurement, but not counted among the object particles, and only taken into account as representing the disturbance of the system which the carrying out of a measurement implies. The energy m_0c^2 belongs to the physical origin contemplated as a virtual particle, and gives it a proper mass m_0 . In order that quantum equations may be definite, the uncertainty constants ε and m_0 of the physical origin must have standard values. [中文](#)

Naturally physicists who have neglected the uncertainty ε of the origin will find that their equations break down at distances of order ε . Nothing has gone wrong with space; it is the theorists who have failed to apply their own principles in relating the observable physical system to space. To state their failure summarily: there are two recognized principles of observability, namely, the quantum principle that an observable *object* has an uncertainty relation to the geometrical space-time frame, and the relativity principle that an observable *quantity* relates to two observable objects. Current theory

recognizes these principles separately but not in combination; and in dealing with co-ordinates and momenta it pays attention only to the uncertainty at the object-particle end of the relation. 中文

The remedy is obvious. I do not say that the application of the remedy is an easy matter; but, if it is clearly the thing most worth doing, that will not deter anyone. An astronomer, unable to solve his own “problem of three bodies”, can only admire the success with which physicists tackle the more numerous closely interacting particles of the nucleus. But I think the advance would not be less rapid or less substantial if they gave up using the wrong formulae. My own work¹ (chiefly concerned with the momentum uncertainty m_0) has been confined to extra-nuclear problems; no insuperable difficulty has appeared, though progress has not been easy. 中文

I turn now to the actual values of ε and m_0 . A geometrical frame of space-time is not a physical reference system, since its exactitude is incompatible with observability. (To assign infinite mass to the frame, so as to make both its position and velocity exact, would introduce infinite curvature, and defeat its use in a different way.) We turn it into a physical frame by associating with it uncertainty constants, namely, a particular length ε and a particular mass m_0 . (In mathematical treatment we should assign to the frame a wave function describing a probability distribution corresponding to these constants.) These “put the scale into” physical systems, and all other natural lengths and masses will stand in a definite numerical ratio to them. Since we observe only relative scale, the arbitrariness of the initial choice of ε and m_0 is eliminated. From extra-nuclear investigations I have found that m_0 is 10/136 of the mass of a hydrogen atom; and ε , which is very simply related to certain magnitudes calculated in cosmological theory², has the value 1.10×10^{-13} cm. (For technical reasons, the constant more usually given is $k_0 = 2\varepsilon = 2.20 \times 10^{-13}$ cm.) 中文

That the virtual particle of mass m_0 , originally studied in extra-nuclear theory, is the particle now used in nuclear theory under the name of “mesotron”, or “meson”, admits, I think, of no doubt. But whether the usual assumption is correct, that nuclear mesotrons are the same as the actual mesotrons observed in a Wilson chamber, I have no means of judging. Since m_0 and ε are conjugate, it is optional which we treat as the more fundamental; but I would point out that to proceed *via* the mesotron mass is a roundabout way of getting at the range of nuclear forces, since the range is an immediate manifestation of the uncertainty of position of the origin. The nuclear force between two protons comes from an energy-singularity occurring when two protons coincide—a sink which (in uniform distribution) just compensates the Coulomb energy occurring when they do not coincide. The condition of coincidence $\xi = 0$ gives $\xi_0 = \pm \varepsilon \sqrt{2}$, which (for the calculated value of ε) agrees exactly with the range of force found by Breit, Condon and Present in their discussion of the scattering of protons.

中文

(143, 432-433; 1939)

A. S. Eddington: Observatory, Cambridge, Feb. 27.

References:

1. Eddington, “Relativity Theory of Protons and Electrons”, Chapters XI, XII.
2. Eddington, *Proc. Roy. Soc., A*, **162**, 155 (1937).

短程和高能中量子理论的“失败”

爱丁顿

阿瑟·爱丁顿是英国迄今为止最杰出的天文学家。后来他将注意力转向了新量子力学所引发的问题上。巴巴声称量子力学不适用于高能原子粒子的行为，爱丁顿随即对这一观点作出了回应。他阐述了理论上如何描述所有的原子核，进而认为量子力学没必要修正。不过遗憾的是巴巴和爱丁顿都没有意识到，当在他们的理论中引进介子后，相应会出现的一些新的问题。 [英文](#)

在2月18日《自然》杂志上巴巴博士的文章中，提到了量子理论在短程和高能中存在问题。这似乎可以广泛的解释为需要对我们现有的物理概念的有效性做出限定。某些问题确实与基本的时间和空间结构的不连续性相关。现在严苛地质疑巴巴博士的文章还为时过早，就该文而言，它与更极端的解释相反。但我要冒昧地提出一个小的疑问，即究竟什么才真正是相对论的基本点。简言之，我们知道为什么现有的理论已经处于困境，并且我们也知道如果要克服这些困难必须要考虑什么。

[英文](#)

相对论以否认绝对运动为出发点。每一个我们观测到的速度 dx/dt 都是两个物理对象的相对速度。同样地，“ x ”是两个物理对象之间的相对位移，而速度是“ x ”对时间的一阶导数。两个物体都与海森堡所指出的时空框架相联系；即它们并不是像三维空间中的点（或四维时空中的世界线）那样有确定的位置，它们的位置和动量具有不确定性。 [英文](#)

通常， dx/dt 和 x 赋予其中一个物体（本文称之为实物粒子），另一个则被视为是参照物。显然，在精确的公式中，参照物必须是一个粒子。这个参照粒子即为物理“原点”，我们可以由此测量实物粒子的可观测量 x 。目前的量子理论已重复了相对论前时期的错误，即对精确公

式所对应的物理参考系的定义不够重视。该理论虽然清楚地表达了包含 x 和 $\partial/\partial x$ 的公式，但却忽略了对 x 所参照的原点的位置和动量的标准偏差（不确定度）的测定。显然，公式并不可能对任意的一个标准偏差都是正确的；如果公式正确，它必然对应于特定位置的标准偏差 ε ，并且这个标准偏差也应当已确定。由于不存在明确的参照系， ε 的实际值必然隐含在量子公式的经验常数（例如 h/mc ）中。 [英文](#)

当考虑分别位于坐标 x_1 和 x_2 中的两个实物粒子时，一个粒子相对于另一个粒子的位移 ξ_0 是可观察的，这与任何坐标原点无关，也就是本文第二段中称为“ x ”的原始可观测量。一定不要把它与坐标差 $\xi = x_2 - x_1$ 相混淆，坐标差引入了测量 x_1 和 x_2 时所参照的物理原点两倍的不确定度。我们得到（用误差理论的符号表示）

$$\xi = \xi_0 \pm \varepsilon \sqrt{2}$$

目前理论的失败主要是忽略了两个可观测量 ξ 和 ξ_0 的区别所致。 [英文](#)

物理原点具有位置和动量两种不确定度；因为如果其中任意一个物理量为零，那么另一个物理量必将是无穷大，那么物理原点就不会以有限的世界线接近几何原点。因此，存在一个对应于不确定动量均方值的能量 $m_0 c^2$ 与原点相联系。除了在二体问题中（其中一个实物粒子作为另一个的物理原点），实际上对所有的物体粒子都作无差别处理；我们用一个附加的虚粒子作为物理原点，即把一个粒子作为测量装置的一部分插入到系统中，但不计入实物粒子，而仅将其作为测量时所包含的系统扰动来考虑。能量 $m_0 c^2$ 对应于虚粒子考虑的物理原点，并给出其固有质量 m_0 。为了可以确定量子方程，物理原点的不确定量 ε 和 m_0 必须具有标准值。 [英文](#)

当然，忽略了原点不确定度 ε 的物理学家将会发现，他们的方程在量级为 ε 时会失效。空间本身没有问题；问题出在那些理论工作者身上，他们无法成功地应用自己的理论将可观测的物理系统与空间相联系。他们的失败可以概括地表述为：存在两个公认的关于可观测性的原理，即量子理论和相对性原理，在前者中可观测的物体对几何时空框架

具有不确定关系，在后者中可观测的量与两个可观测的物体相关。目前的理论认为，这些原理相互独立无法结合；当我们处理坐标和动量时，仅需注意其关系中实物粒子端的不确定度。 [英文](#)

补救措施是明显的。我并不是说完成修正是一件简单的事情；但是，如果它是一件最值得去做的事情，那就不会使任何人畏缩不前。一位不能解决自己“三体问题”的天文学家，只能羡慕物理学家处理原子核中大量存在短程相互作用的粒子时所取得的成就。但我认为，如果他们放弃使用错误的公式，不会使进展速度变缓，或使进展的实质性减弱。我自己的工作^[1]（主要是关于动量不确定量 m_0 ）一直局限于核外问题；在此过程中虽然尚未出现不能克服的困难，但也是举步维艰。 [英文](#)

现在我回到 ε 与 m_0 的实际值问题的讨论。时空的几何框架并不是物理参考系，因为其精确性与可观测性互不相容。（设框架质量无限大，以使其位置和速度两者的值均是精确的，但这将引出无限曲率，使得该框架以另外一种方式失效。）我们将它转化为具有不确定性常数的物理框架，即其中的不确定性常数就是特定的长度 ε 和特定的质量 m_0 。（在数学处理中，我们应赋予框架一个波函数来描述与这些常数相应的概率分布。）对物理系统“进行标度变换”，即所有其他自然长度和质量将以其成确定比率的数值形式出现。由于我们仅观测相对标度，排除了 ε 和 m_0 最初选择的任意性。根据核外研究我发现， m_0 是氢原子质量的 $10/136$ ； ε 与宇宙论^[2]中计算得到的确定量值有非常简单的关系，数值为 1.10×10^{-13} 厘米（出于技术方面的考虑，通常将常数取为 $k_0 = 2\varepsilon = 2.20 \times 10^{-13}$ 厘米）。 [英文](#)

最初在核外理论中研究的质量为 m_0 的虚粒子，正是现在核理论中的“介子”，我认为这种观点是毋庸置疑的。但通常的假设是否正确，即核介子是否与威尔逊云室中观测到的实际介子相同，我还无法做出判断。由于 m_0 与 ε 是共轭的，因此选择哪个作为基本量是任意的；但我要指出的是，由介子的质量出发确定核力的作用范围是一种不直接的方式，因为此范围是原点位置不确定性的直接表现。在两个质子之间的核力来自两个质子重合时产生的能量奇点——一个下陷，它（在均匀分布中）刚好可以补偿两个质子不重合时产生的库仑能。在刚好符合 $\xi=0$ 的条件时，有 $\xi_0 = \pm \varepsilon \sqrt{2}$ ，这（在 ξ 的计算值方面）与布莱特、康登和普

雷森特在他们对质子散射的论述中建立的力的范围精确地一致。 英文

（沈乃澂 翻译；鲍重光 李军刚 审稿）

Liberation of Neutrons in the Nuclear Explosion of Uranium

H. von Halban, jun. *et al.*

Recent experiments had shown that considerable energy was released in the explosion of uranium or thorium nuclei, triggered by impacting neutrons. The possibility of an energy-releasing chain reaction depended on whether such processes might release further neutrons. Here Hans von Halban, Frédéric Joliot and Lew Kowarski report experiments suggesting a positive answer. They sent neutrons into two substances, ammonium nitrate and uranyl nitrate, and measured the number of detected slow neutrons as a function of distance. A discrepancy between the two substances clearly seemed attributable to the presence of uranium and to additional neutrons being created in fission events. They could say little about the energy of the neutrons, but these observations were a step towards sustained nuclear fission. [中文](#)

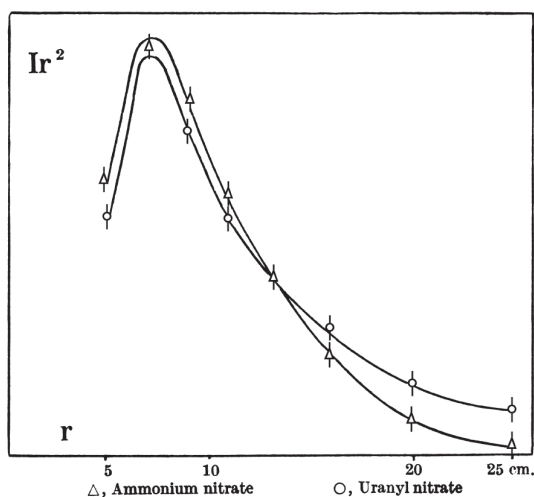
RECENT experiments^{1,2} have revealed the existence of a new kind of nuclear reaction: neutron bombardment of uranium and thorium leads to an explosion of the nucleus, which splits up into particles of inferior charge and weight, a considerable amount of energy being liberated in this process. Assuming a partition into two particles only, so that the nuclear mass and charge of uranium have to be distributed between two lighter nuclei, the latter contain considerably more neutrons than

the heaviest stable isotopes with the same nuclear charges. (A splitting into, for example, ^{98}Rb and ^{141}Cs means an excess of 11 neutrons in the first, and of 8 neutrons in the second of these two nuclei.) There seem to be two possibilities of getting rid of this neutron excess. By the emission of a β -ray, a neutron is transformed into a proton, thus reducing the neutron excess by two units; in the example given above, five and four successive β -activities respectively would be needed to restore the neutron-proton stability ratio. In fact, the explosion products have been observed to be β -active and several periods have been recorded, so that a part, at least, of the neutron excess is certainly disposed of in this way. Another possible process is the direct liberation of neutrons, taking place either as a part of the explosion itself, or as an "evaporation" from the resulting nuclei which would be formed in an excited state. [中文](#)

In order to find some evidence of this second phenomenon, we studied the density distribution of the thermal neutrons produced by the slowing down of photo-neutrons from a Ra γ -Be source in a 1.6 molar solution of uranyl nitrate and in a 1.6 molar solution of ammonium nitrate (the hydrogen contents of these two solutions differ by only 2 percent). Plotting Ir^2 as a function of r (where r is the distance between the source and a given point, and I is the local density of thermal neutrons at the same point, measured by the activity induced in a dysprosium detector), a curve is obtained the area of which is proportional to $Q\tau$, Q being the number of neutrons per second emitted by the source or formed in the solution and τ the mean time a neutron spends in the solution before being captured^{3,4}. Any additional nuclei, which do not produce neutrons, brought into the solution, will increase the chances of capture and therefore decrease τ and the area. If, however, these dissolved nuclei are neutron-producing, Q will be greater and the area of the curve will tend to increase. Evidence of neutron production, as indicated by an actual increase of the area, will only be obtained if the gain through Q

(neutron production) is greater than the loss through τ (neutron capture). This loss can anyway be studied separately, since it has been shown⁵ that the introduction of nuclei which act merely by capture or by increasing the hydrogen content of the solution can affect the shape of the density curve only in a characteristic way: the modified curve can always be brought to coincide with the primitive curve by multiplying all abscissae by a suitable factor and all ordinates by another factor. 中文

The accompanying graph shows the two curves obtained. At small distances from the source the neutron density is greater in the ammonium solution than in the uranyl solution; at distances greater than 13 cm., the reverse is true. In other words, the decrease of the neutron density with the distance is appreciably slower in the uranyl solution. 中文



中文

The observed difference must be ascribed to the presence of uranium. Since the two curves cannot be brought to coincide by the transformation mentioned above, the uranium nuclei do not act by capture only; an *elastic* diffusion by uranium nuclei would have an opposite effect: it would “contract” the abscissae, instead of stretching

them. The density excess, shown by the uranyl curve beyond 13 cm., must therefore be considered as a proof of neutron production due to an interaction between the primary neutrons and the uranium nuclei. A reaction of the well-known (n , $2n$) type is excluded because our primary neutrons are too slow for such a reaction (90 percent of Ra + Be photo-neutrons have energies smaller than 0.5 Mev. and the remaining 10 percent are slower than 1 Mev.). 中文

The degree of precision of the experiment does not permit us to attribute any significance to the small increase of the area in the uranyl curve (as compared to the ammonium curve), which we obtain by extrapolating the curves towards greater distances. In any event, an inferior limit for the cross-section for the production of a neutron can be obtained by assuming that the density excess due to this production is equal throughout the whole curve to the excess observed at $r = 25$ cm.; this limit, certainly inferior to the actual value, is 6×10^{-25} cm.².

中文

Our measurements yield no information on the energy of the neutrons produced. If, among these neutrons, some possess an energy superior to 2 Mev., one might hope to detect them by a (n,p) process, for example, by the $^{32}\text{S}(n,p)^{32}\text{P}$ reaction. An experiment of this kind, Ra γ -Be still being used as the primary neutron source, is under way. 中

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The interest of the phenomenon observed as a step towards the production of exo-energetic transmutation chains is evident. However, in order to establish such a chain, more than one neutron must be produced for each neutron absorbed. This seems to be the case, since the cross-section for the liberation of a neutron seems to be greater than the cross-section for the production of an explosion. Experiments with solutions of varying concentration will give information on this question. 中文

H. von Halban, jun., F. Joliot and L. Kowarski: Laboratoire de Chimie Nucléaire, Collège de France, Paris, March 8.

References:

1. Joliot, F., *C.R.*, **208**, 341 (1939).
2. Frisch, O. R., *Nature*, **143**, 276 (1939).
3. Amaldi, E., and Fermi, E., *Phys. Rev.* **50**, 899 (1936).
4. Amaldi, E., Hafstad, L., and Tuve, M., *Phys. Rev.*, **51**, 896 (1937).
5. Frisch, O. R., von Halban, jun., H., and Koch, J., *Danske Videnskab. Kab.*, **15**, 10 (1938).

铀核爆炸时中子的释放

冯·哈尔班等

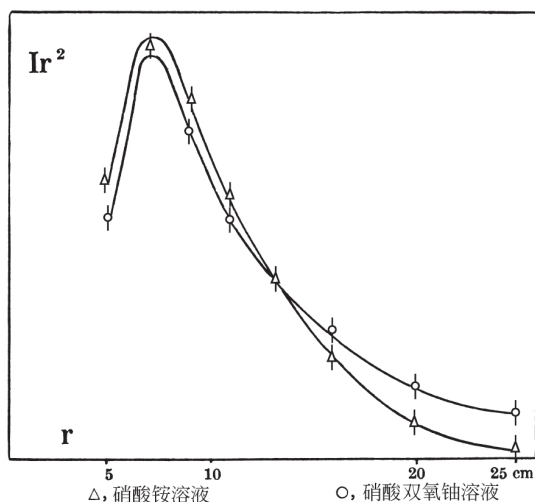
最近的实验显示由中子碰撞触发的铀核或钚核爆炸释放出相当多的能量。释放能量的链式反应发生的可能性依赖于这个过程是否释放更多的中子。本文中，汉斯·冯·哈尔班、弗雷德里克·约里奥和卢·科瓦尔斯基称实验给出了肯定答案。他们用中子轰击硝酸铵和硝酸双氧铀两种物质，对观测到的慢中子数目随距离的变化进行测量。在两种物质中产生的差异无疑是因为铀核的存在和在裂变中产生的额外中子。关于中子能量他们能讲得很少，但是这些观测是迈向持续核裂变研究的一步。 [英文](#)

最近的实验^[1,2]已经揭示了存在一种新的核反应：用中子轰击铀和钚会引发核爆炸，核分裂为电荷和质量较小的粒子，同时在这个过程中释放了相当大的能量。假设一次分裂仅产生两个粒子，则铀核的质量和电荷必定在两个更轻的核之间分配，与带有相同核电荷的最重的稳定同位素相比，两个轻核含有较多的中子。（例如，分裂为⁹⁸Rb和¹⁴¹Cs意味着在两个核子中，第一个核子多出了11个中子，第二个核子多出了8个中子。）似乎存在着两种可能性来消除这些过剩中子。通过发射 β 射线，一个中子转变为一个质子，这样就减少了两个单位的过剩中子；在上述给出的例子中，分别需要相继5次和4次 β 放射来恢复中子-质子的稳定率。实际上，已观测到的爆炸产物是具有 β 活性的，并且已经记录到了几个活性周期。因此，至少有一部分过剩的中子必定是通过这种方式去除的。另一种可能的过程是中子以部分爆炸产物的形式被直接释放，或从处于激发态的生成核中“蒸发”掉。 [英文](#)

为了找到这类次级现象的某些证据，我们研究了Ra- γ -Be光中子在1.6摩尔硝酸双氧铀溶液和1.6摩尔硝酸铵溶液中的减速所产生的热中子

的密度分布（这两种溶液中的氢含量只相差2%）。将 Ir^2 作为 r 的函数绘图（其中 r 是源点与给定点之间的距离， I 是热中子在相同点的局部密度，通过镱探测器中感生到的放射性进行测量），图中所得曲线的面积与 $Q\tau$ 成正比， Q 是每秒由中子源发射出的或在溶液中形成的中子数， τ 是中子被俘获之前在溶液中度过的平均时间^[3,4]。将任何其他不产生中子的原子核放入溶液中将会增加中子被俘获的概率，因此时间 τ 和面积也会相应减小。然而，如果溶液中的这些核是产生中子的，那么 Q 将更大，曲线的面积也将趋于增大。由面积的实际增大所表明中子生成的证据将仅在以下情况中才能获得，即由 Q （中子生成）所造成的增益比由时间 τ （中子俘获）所导致的损耗大的情况。我们可以通过各种方式来分别研究这项损耗，因为其已经表明^[5]，仅仅是通过俘获，或通过增加溶液中的氢含量而引入的核只通过一种特定的方式来影响密度曲线的形状，那么将原始曲线的所有横坐标乘上一个合适的因子，而将纵坐标乘上另一个合适的因子，修正的曲线总能与其相吻合。 英文

附图显示了得到的两条曲线。在与源距离较近的位置，硝酸铵溶液中的中子密度大于硝酸双氧铀溶液中的密度；但在距离大于13厘米的位置时，情况则相反。换言之，在硝酸双氧铀溶液中中子密度随距离的减小明显较为缓慢。 英文



英文

观测到这样的差别一定是由铀的存在所致。因为这两条曲线不能通

过上述修正而重合，所以铀核不仅仅起俘获的作用；由铀核所产生的弹性漫射将会起到相反的效果：它会“缩短”横坐标，而不是延长横坐标。因此，当距离超过13厘米时硝酸双氧铀曲线所示的密度超量，必定会被当作中子是由初级中子与铀核之间的相互作用的产物的证据。熟知的 $(n, 2n)$ 型的反应是被排除在外的，这是由于对于这类反应而言我们的初级中子的能量太小了（90%的Ra + Be光中子的能量小于0.5兆电子伏，其余的10%小于1兆电子伏）。 [英文](#)

实验的精度不允许我们对硝酸双氧铀曲线中面积的微小增加（与硝酸铵曲线比较）赋予任何含义，这样的增加是我们将曲线向距离更大的方向外推时得到的。在任何情况下，假设由于中子产生造成的密度增量等于在 $r = 25$ 厘米处观测到的整个曲线的增量，则可得到中子产生的截面下限；这个极限肯定在实际值之下，为 6×10^{-25} 平方厘米。 [英文](#)

我们的测量还无法给出关于所产生中子的能量的信息。如果在这些中子之中，某些中子具有的能量超过2兆电子伏，我们有望通过一个 (n, p) 过程来探测它们，例如，通过 $^{32}\text{S}(n, p)^{32}\text{P}$ 反应。初级中子源仍然为Ra γ -Be的这种实验正在进行之中。 [英文](#)

我们所观测的现象使实现产生外能变换链向前迈进了一步，这个意义是很明显的。然而，为了建立这样的链条，每吸收一个中子，都必须再产生一个以上的中子。看起来事实就是如此，因为释放一个中子的截面似乎大于产生一次爆炸的截面。采用各种不同浓度的溶液进行的实验将给出该问题的相关信息。 [英文](#)

（沈乃澂 翻译；王乃彦 审稿）

Products of the Fission of the Uranium Nucleus

L. Meitner and O. R. Frisch

Lise Meitner and Otto Frisch here report new experiments probing the products of uranium fission experiments. Earlier work suggested that fission fragments should emerge with energies of several hundred million electron volts. Here the researchers sent neutrons into a sample of uranium hydroxide and attempted to collect the fission fragments 1 mm away, either in a paper surface or in water. They found evidence for a range of different fission fragments. It seemed most unlikely that the mere absorption of a neutron could give a uranium nucleus enough kinetic energy to reach their collecting surfaces. This new technique offered a route to the more detailed examination of the nuclear fragments created in fission processes. [中文](#)

O Hahn and F. Strassmann¹ have discovered a new type of nuclear reaction, the splitting into two smaller nuclei of the nuclei of uranium and thorium under neutron bombardment. Thus they demonstrated the production of nuclei of barium, lanthanum, strontium, yttrium, and, more recently, of xenon and caesium. [中文](#)

It can be shown by simple considerations that this type of nuclear reaction may be described in an essentially classical way like the fission of a liquid drop, and that the fission products must fly apart

with kinetic energies of the order of hundred million electron-volts each². Evidence for these high energies was first given by O. R. Frisch³ and almost simultaneously by a number of other investigators⁴. 中文

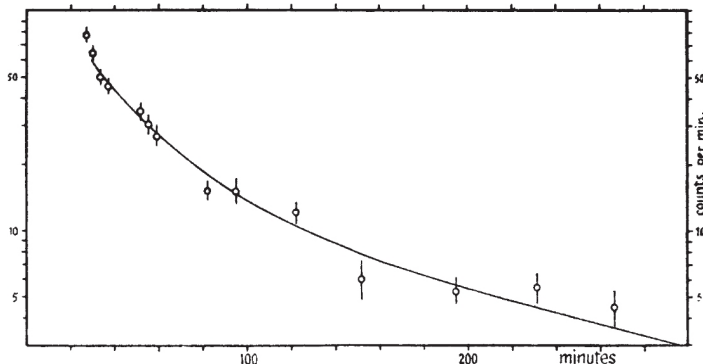
The possibility of making use of these high energies in order to collect the fission products in the same way as one collects the active deposit from alpha-recoil has been pointed out by L. Meitner (see ref. 3). In the meantime, F. Joliot has independently made experiments of this type⁵. We have now carried out some experiments, using the recently completed high-tension equipment of the Institute of Theoretical Physics, Copenhagen. 中文

A thin layer of uranium hydroxide, placed at a distance of 1 mm. from a collecting surface, was exposed to neutron bombardment. The neutrons were produced by bombarding lithium or beryllium targets with deuterons of energies up to 800 kilovolts. In the first experiments, a piece of paper was used as a collecting surface (after making sure that the paper did not get active by itself under neutron bombardment). About two minutes after interrupting the irradiation, the paper was placed near a Geiger-Müller counter with aluminium walls of 0.1 mm. thickness. We found a well-measurable activity which decayed first quickly (about two minutes half-value period) and then more slowly. No attempt was made to analyse the slow decay in view of the large number of periods to be expected. 中文

The considerable intensity, however, of the collected activity encouraged us to try to get further information by chemical separations. The simplest experiment was to apply the chemical methods which have been developed in order to separate the "transuranium" elements from uranium and elements immediately below it⁶. The methods had to be slightly modified on account of the absence of uranium in our samples and in view of the light element activities discovered by Hahn and Strassmann¹. 中文

In these experiments, the collecting surface was water, contained in a shallow trough of paraffin wax. After irradiation (of about one hour) a small sample of the water was evaporated on a piece of aluminium foil; its activity was found to decay to zero. It was checked in other ways, too, that the water was not contaminated by uranium. To the rest of the water we added 150 mgm. barium chloride, 15 mgm. lanthanum nitrate, 15 mgm. platinum chloride and enough hydrochloric acid to get an acid concentration of 7 percent. Then the platinum was precipitated with hydrogen sulphide, in the usual way; the precipitate was carefully rinsed and dried and then placed near our counter. 中文

The results of three such experiments were found to be in mutual agreement. The decay of the activity was in one case followed for 28 hours. For comparison, a sample of uranium irradiated for one hour was treated chemically in the same way. The two decay curves were in perfect agreement with one another and with an old curve obtained by Hahn, Meitner and Strassmann under the same conditions. In the accompanying diagram the circles represent our recoil experiment while the full line represents the uranium precipitate. A comparison of the activity (within the first hour after irradiation) of the precipitate and of the evaporated sample showed that the precipitate contained about two thirds of the total activity collected in the water. After about two hours, however, the evaporated sample was found to decay considerably more slowly than the precipitate, presumably on account of the more long-lived fission products found by Hahn and Strassmann¹. 中文



中文

From these results, it can be concluded that the “transuranium” nuclei originate by fission of the uranium nucleus. Mere capture of a neutron would give so little kinetic energy to the nucleus that only a vanishing fraction of these nuclei could reach the water surface. So it appears that the “transuranium” periods, too, will have to be ascribed to elements considerably lighter than uranium. 中文

In conclusion, we wish to thank Dr. T. Bjerge, Dr. J. Koch and K. J. Brostrøm for putting the high-tension plant at our disposal and for kind help with the irradiations. We are also grateful to Prof. N. Bohr for the hospitality extended to us at the Institute of Theoretical Physics, Copenhagen. 中文

(143, 471-472; 1939)

Lise Meitner: Physical Institute, Academy of Sciences, Stockholm.

Otto Robert Frisch: Institute of Theoretical Physics, University, Copenhagen, March 6.

References:

1. Hahn, O., and Strassmann, F., *Naturwiss.*, **27**, 11, 89, and 163 (1939).
2. Meitner, L., and Frisch, O. R., *Nature*, **143**, 239 (1939). Bohr, N., *Nature*, **143**, 330 (1939).
3. Frisch, O. R., *Nature*, **143**, 276 (1939).
4. Fowler, R. D., and Dodson, R. W., *Nature*, **143**, 233 (1939). Jentschke, W., and Prankl, F., *Naturwiss.*, **27**, 134 (1939).
5. Joliot, F., C. R., **208**, 341 (1939).

6. Hahn, O., Meitner, L., and Strassmann, F., *Chem. Ber.*, **69**, 905 (1936); and **70**, 1374 (1937).

铀核的裂变产物

迈特纳，弗里施

莉泽·迈特纳和奥托·弗里施在这篇文章中报道了关于探测铀核裂变产物的新实验。早期的研究认为裂变碎片的产生会伴随有几百兆电子伏的能量出现。本文作者用中子轰击氢氧化铀样品，尝试在1毫米远的纸张表面或者水中收集裂变碎片。他们发现了一系列不同的裂变碎片存在的证据。可以看出，仅靠吸收一个中子似乎不能提供铀原子核足够的动能使其到达他们的收集表面。这项新技术提供了一个途径去更仔细地检测裂变过程中产生的原子核碎片。 [英文](#)

哈恩和施特拉斯曼^[1]发现了一种新型核反应，即在中子轰击下，铀核和钍核分裂为两个更小的核。以此他们证明了钡核、镧核、铈核、钇核以及最近又发现的氙核和铯核等裂变产物。 [英文](#)

可以简单地以一种本质上经典的方式，比如类似于液滴分裂的形式，来描述这类核反应，并且分裂的产物必定以上百兆电子伏的动能飞离^[2]。弗里施^[3]首先给出这些高能反应的证明，几乎是在同一时间其他多位研究者也给出了证明^[4]。 [英文](#)

迈特纳已经指出（见参考文献3），像人们从 α 反冲中收集放射性沉积物那样，利用这些高能量来收集裂变产物是可能的。在此期间，约里奥已独立地进行了这类实验^[5]。我们利用哥本哈根理论物理研究所最近制成的高压装置，现在已经开展了一些实验。 [英文](#)

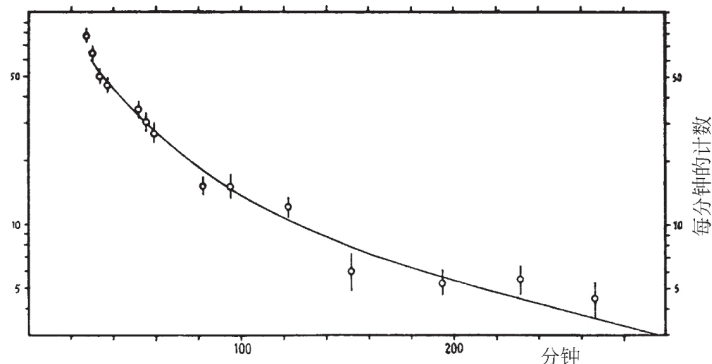
将一薄层氢氧化铀放在距收集表面1毫米的位置，并用中子对其进行轰击。中子是用能量高达800千电子伏的氘核轰击锂靶或铍靶而产生的。在第一个实验中，使用一张纸作为收集表面（已经确定纸在经过中子轰击后纸本身不具有放射性）。在辐照中断大约两分钟后，将纸放在

具有0.1毫米厚铝壁的盖革-米勒计数器的附近。我们发现放射性可以很好地被测量到，并且开始时放射性衰变得很快（约两分钟的半衰期），然后会较为缓慢。鉴于估计其中存在数目繁多的周期，我们并不打算对缓慢的衰变进行分析。 [英文](#)

然而，收集到的放射性有相当大的强度，这促使我们试图通过化学分离的方法得到更进一步的信息。最简单的实验是采用一种化学方法，最初发展这种方法是为了把所谓的“超铀”元素从铀及紧邻它的较低的元素中分离出来^[6]。考虑到在我们的样品中不存在铀，并鉴于哈恩和施特拉斯曼^[1]发现的轻元素的放射性，这种实验方法必须稍做改进。 [英文](#)

这些实验均以石蜡浅槽中的水作收集表面。在（大约一小时的）辐照后，少量样品水被蒸发到一片铝箔上；并且其放射性衰变为零。用其他方法也可证明这些水中并不含铀。在剩余的水中，我们加入150毫克氯化钡、15毫克硝酸镭、15毫克氯化铂和足够的盐酸，以便得到7%的酸浓度。采用通常的方法，用硫化氢将铂析出；析出的沉淀物经过精心漂洗和烘干，然后放在我们的计数器附近。 [英文](#)

我们发现三个这样的实验得到的结果是相互一致的。在其中一种情况下，对放射性物质的衰变跟踪了28小时。作为对照，对经过一个小时辐照的铀样品，按同样方式进行化学处理。结果显示，这两条衰变曲线完全一致，并且它们与之前由哈恩、迈特纳和施特拉斯曼在相同条件下得到的曲线也完全符合。在附图中，圆圈表示我们的反冲实验，而实线表示铀的沉淀物。沉淀物与经过蒸发样品的放射性（辐照后的第一小时内）的对比表明，沉淀物大约含有水中收集到的总放射性的2/3。然而，在大约两小时后，我们发现经过蒸发的样品比沉淀样品的衰变要更加缓慢，这大概是由哈恩和施特拉斯曼^[1]所发现的更长寿命的裂变产物所致。 [英文](#)



英文

根据这些结果我们可以断定，所谓“超铀”核是由铀核裂变产生的。仅仅俘获一个中子只能为核提供极少的动能，因此这些核中没有一个能够达到水的表面。因而所谓“超铀”周期似乎也必然是由比铀轻得多的元素所致。

英文

最后，我们要感谢伯格博士、科赫博士和布罗斯特伦，他们将高压设备交给我们自由使用并好心地对实验中的辐照提供了帮助。我们同样对玻尔教授在哥本哈根理论物理研究所对我们的热情款待表示感激。

英文

（沈乃澂 翻译；张焕乔 审稿）

New Products of the Fission of the Thorium Nucleus

L. Meitner

In late 1938, German physicists Otto Hahn and Fritz Strassmann in Berlin discovered nuclear fission: the splitting of large atomic nuclei such as uranium into smaller fragments, with an immense release of energy. Production of neutrons during uranium fission meant that the process could be self-sustaining: in reactors and in a bomb. Hahn and Strassmann had been working with the Austrian physicist Lise Meitner, but as a Jew she had been forced to flee from the Nazi regime that summer. Here Meitner, now in Stockholm, extends that work by showing that the element thorium can also undergo fission, and that both uranium and thorium fission lead to similar end products. Hahn was later awarded the Nobel prize for the discovery of fission, but it is now acknowledged that Meitner's contributions were vital to understanding the process. [中文](#)

IN a preceding communication¹ it has been shown that the “transuranium” elements are found among the fission products of uranium under neutron bombardment. Consequently they must be lower elements, probably partly somewhere near tellurium², partly (the complementary fission fragments) in the region of ruthenium.

[中文](#)

It was then natural to carry out similar experiments with thorium in order to see whether the fission of thorium gave rise to elements with chemical properties similar to those of the “transuranium” elements, that is, elements which can be precipitated with hydrogen sulphide from a strong hydrochloric acid solution. No search for such elements had previously been carried out with thorium, since the formation of elements beyond uranium, from thorium, was not to be expected. So far, chemical analysis of the radioactive bodies produced in thorium by neutron bombardment has revealed (apart from a thorium and a protactinium isotope resulting from pure neutron capture) only products which, on the basis of their chemical properties, had originally to be assigned to radium and actinium isotopes³ and which have more recently been identified with barium and lanthanum isotopes⁴. 中文

A “thick” layer of thorium oxide on a glass plate was irradiated by neutrons obtained by bombarding a lithium target with deuterons of 800 kv. from the high-tension equipment of the Institute of Theoretical Physics, Copenhagen. In order to collect the recoil nuclei, a water surface was used in the way previously described¹. After irradiation (of about one hour) a fraction (2 c.c.) of the water was evaporated without chemical separation; with the rest (9 c.c.) the usual hydrogen sulphide precipitation was carried out in exactly the same way as in the uranium recoil experiments¹. 中文

The precipitate showed a clearly measurable activity, the decay of which was distinctly different from the decay of the analogous uranium products. After an initial decrease with a half-value period of about 40 minutes, an activity remained which was followed for almost two days and showed a single decay period of 14–15 hours. The evaporated sample showed first a much faster decay which then gradually became slower; after two days, the activity had vanished.

中文

A second experiment with 2.5 hours' irradiation gave the same result, with correspondingly greater intensity, especially of the longer period. In this experiment, after the sulphide precipitation, the filtrate was neutralized and the barium and lanthanum¹ were precipitated as carbonates. The carbonate precipitate decayed first with about 20 minutes and then with 4 hours half-value period, in agreement with the periods already known^{3,4}. Analysis of the decay of the sulphide precipitate showed again the presence of a substance of half-period about 40 minutes and of one of 14.5 hours, which was followed for nearly three days and found to decay to zero. The initial intensities of the two periods were about equal, in spite of the short duration of bombardment. The possible existence of very short or very long additional periods can, of course, not be excluded on the basis of this experiment. The two periods observed are quite different from those of the chemically analogous uranium products. [中文](#)

Several check experiments without neutrons showed that there was no contamination of the water by thorium B or C, which might have resulted from radioactive recoil or traces of emanating thoron. As a further protective measure, the thorium layer was sealed, in the second experiment, by a celluloid membrane of 0.3 mm. stopping power. [中文](#)

From the evidence given above, one can conclude that some of the fission products of thorium show a chemical behaviour similar to that of the "transuranium" elements. This is a further indication that essentially the same chemical elements are produced in the fission of uranium and thorium. [中文](#)

In conclusion, I wish to express my thanks to Dr. T. Bjerger, Dr. J. Koch, and K. J. Brostrøm for kind help in the irradiations with the high-tension tube. I am especially grateful to Prof. N. Bohr for the opportunity to carry out these experiments and for the facilities kindly put at my disposal at the Institute of Theoretical Physics, Copenhagen.

Lise Meitner: Physical Institute, Academy of Sciences, Stockholm, March 26.

References:

1. Meitner, L., and Frisch, O. R. *Nature*, **143**, 471 (1939).
2. Abelson, P., *Phys. Rev.*, **55**, 418 (1939). Feather, N., and Bretscher. E., *Nature*, **143**, 516 (1939).
3. Meitner, L., Hahn, O., and Strassmann, F., *Phys., Z.* **109**, 538 (1938).
4. Hahn, O., and Strassmann, F., *Naturwiss.*, **27**, 89 (1939).

钍核裂变的新产物

迈特纳

1938年末，德国物理学家奥托·哈恩和弗里茨·施特拉斯曼在柏林发现了核裂变：大原子核（例如铀核）分裂成较小的碎片，并释放出大量能量。铀裂变过程中产生了中子，意味着无论在反应堆中还是在原子弹中，该过程都是可以自持的。哈恩和施特拉斯曼一直以来都与奥地利物理学家莉泽·迈特纳保持合作，但迈特纳作为犹太人，被迫于1938年夏天逃离纳粹统治区。本文中，已经来到了斯德哥尔摩的迈特纳延续了上述工作。她在实验中展示了钍裂变，并发现铀核和钍核裂变都产生相似的最终产物。后来，哈恩因发现裂变而获得了诺贝尔奖。但现在人们认识到，迈特纳的贡献对于理解裂变过程至关重要。 [英文](#)

在此前的一篇通讯^[1]中我们曾指出，在中子轰击下产生的铀的裂变产物中，发现了“超铀”元素。因此它们一定是序数较小的元素，可能部分位于碲附近^[2]，部分（互补的裂变碎片）则位于钇的附近区域。

[英文](#)

于是很自然地我就使用钍来进行类似的实验，目的是看看钍的裂变是否也能产生与“超铀”元素化学性质类似的元素，所谓的“超铀”元素就是那些可以从浓的盐酸溶液中利用硫化氢沉淀下来的元素。此前从未利用钍对这些元素进行过探寻，因为人们从未期望用钍来制得铀后面的元素。迄今为止，对于那些通过中子轰击在钍中产生的放射性物质所做的化学分析表明（除去由单纯的中子俘获所产生的一种钍的同位素和一种镤的同位素之外），只存在这种产物：根据其化学性质，它们最初曾被归为镭和锕的同位素^[3]，但最近已确认其为是钷和镧的同位素^[4]。

[英文](#)

利用哥本哈根理论物理研究所的高压设备，以800千电子伏的氘核轰击锂靶，用所得的中子辐照玻璃板上的氧化钍“厚”涂层。按照以前曾描述过的方法^[1]，利用水的表面来收集反冲核。经过辐照（大约1个小时）后，一部分（2立方厘米）水蒸发但不发生化学分离；对剩余部分（9立方厘米）进行常规的硫化氢沉淀，所用方法与铀反冲实验^[1]中的完全一致。 [英文](#)

沉淀表现出明显的、可测量到的放射性，其衰变显著区别于类似的铀产物的衰变。在经历半衰期约40分钟的初始衰减后，在随后几乎两天仍保持放射性并且表现出单一的14~15小时的半衰期。蒸发的样品最初衰变很快，随后便逐渐减慢；两天后，放射性消失。 [英文](#)

第二次实验经过了2.5小时的辐射，得到了相同的结果，但相应的强度更大一些，尤其是对于更长的周期。在这次实验中，在硫化物沉淀后滤液呈中性，钍和镭^[1]以碳酸盐的形式沉淀。这些碳酸盐最初的半衰期为20分钟，随后变为4小时，这与已知的半衰期^[3,4]相一致。对硫化物沉淀的衰变进行分析，再次表明一种具有40分钟半衰期和一种具有14.5小时半衰期的物质存在，后者持续大约三天，然后消失。尽管轰击持续时间很短，然而两种半衰期的初始强度大致上是相等的。当然，根据这个实验并不能排除存在额外的极短或极长半衰期的可能性。不过我观测到的这两个半衰期与化学性质类似的铀的产物的半衰期全然不同。 [英文](#)

几次无中子辐照的检查性实验表明，水中不存在钍B或钍C（钍B或钍C可能由放射性物质反冲或者极少量钍射气的发射而产生）。为了保险起见，在第二次实验中用阻止本领为0.3毫米的赛璐珞膜将钍层密封。 [英文](#)

根据上面给出的证据可以得出这样的结论，钍的某些裂变产物表现出与“超铀”元素类似的化学特性。这进一步表明在铀和钍的裂变中实质上产生了同样的化学元素。 [英文](#)

最后，我要向伯格博士、科赫博士和布罗斯特伦表示感谢，他们对于高压管辐射实验给予了热心帮助。我还要特别感谢玻尔教授，他使我有机会进行这些实验并慷慨地为我提供了哥本哈根理论物理研究所的实

验设备。

英文

(王耀杨 翻译；朱永生 审稿)

Number of Neutrons Liberated in the Nuclear Fission of Uranium

H. von Halban, jun. *et al.*

Experiments had confirmed that uranium nuclei could be fissioned—induced to split into two large nuclei—when bombarded by a neutron, and that secondary neutrons were given off in the process. But physicists had little idea how many neutrons were produced in such a fission event. This was important to the possibility of a self-sustaining fission chain-reaction. Here physicist Hans von Halban, then working with Frédéric Joliot-Curie and Lew Kowarski in Paris, estimates experimentally how many neutrons are released. The answer—3.5 on average—suggested that a chain reaction might be possible in uranium if the likelihood for a neutron to trigger a fission event were sufficiently high. After the German invasion in 1940, von Halban fled France for England. [中文](#)

RECENT experiments have shown that neutrons are liberated in the nuclear fission of uranium induced by slow neutron bombardment: secondary neutrons have been observed which show spatial¹, energetic² or temporal³ properties different from those which primary neutrons possess or may acquire. Such observations give no information on the mean number of neutrons produced per nucleus

split; this number ν may be very small (less than 1) and the result of the experiment will still be positive. [中文](#)

We are now able to give information on the value of ν . Let us consider the curve representing the density distribution of neutrons slowed down in an aqueous solution surrounding a primary neutron source¹; the area S of this curve is proportional to $Q\tau$, Q being the number of neutrons per second emitted by the source or formed in the solution, and τ the mean time a neutron spends in the solution before being captured. Assuming that the solution contains only nuclei which absorb neutrons according to the $1/v$ law (the only exception to this rule will presently be dealt with), τ is proportional to $1/\Sigma c_i \sigma_i$, where c_i is the concentration (atom grams per litre) of an absorbing nucleus, σ_i its cross-section for the capture of neutrons of velocity 1 and the index i is extended to all kinds of neutron-absorbing reactions attributable to nuclei present in the solution. Substituting the symbol A_i for $c_i \sigma_i$ and A_{tot} for ΣA_i , we have identically:

$$\frac{\Delta S}{S} = \frac{\Delta Q}{Q} - \frac{\Delta A_{tot}}{A_{tot}}, \quad (1)$$

neglecting all terms of higher orders, such as those containing $(\Delta Q)^2$, $\Delta Q \cdot \Delta A_{tot}$, etc. [中文](#)

Let the symbol Δ stand for the differences observed between the two solutions (uranyl and ammonium) used in our previous experiment¹. Neglecting ΔA_{tot} before A_{tot} introduces an ambiguity in the definition of A_{tot} (uranyl vs. ammonium value) which is numerically unimportant and can be reduced by adopting the arithmetical mean $(A_{tot}(\text{amm.}) + \Delta A_{tot})/2$. [中文](#)

In the quantity ΔA_{tot} the uranium nuclei are represented by several separate terms standing for the different modes of neutron capture (see below); let A_f be the term for the capture leading to fission. Every neutron has the probability A_f/A_{tot} of causing a fission and, since one

individual fission process liberates ν neutrons on the average, the total number ΔQ of neutrons thus created is $Q \cdot \frac{A_f}{A_{tot}} \cdot \nu$, and the equation (1) can be rewritten as follows:

$$\nu = \frac{\Delta S}{S} \cdot \frac{A_{tot}}{A_f} + \frac{\Delta A_{tot}}{A_f}. \quad (2)$$

中文

Let us estimate the values of all quantities necessary to calculate ν according to this formula. The area variation $\Delta S/S$ can be read from the graph given in our previous letter with an error of less than 20 percent (due to the uncertainties of inter- and extrapolation; in order to facilitate the latter, we added to the curves a further experimental point for $r = 29$ cm.). The value of A_{tot} for the ammonium solution can be easily calculated from the known concentrations and capture cross-sections (hydrogen, nitrogen and oxygen). A_f is equal to c_U (1.6 in our experiment), multiplied by the value of σ_f given in a recent paper by Anderson *et al.*⁴. ΔA_{tot} contains a term expressing the small difference of the hydrogen content between the two solutions; and three terms relative to uranium, namely, the fission term A_f , already dealt with, the thermal capture term A_{ct} which can be calculated by using a recently found value for σ_{ct} ⁵ and finally the resonance capture term A_r which requires some explanation. 中文

Our reasoning assumed that all neutrons introduced into the solution spend practically all their life, and are absorbed, in the thermal state. This is true in so far as the $1/\nu$ law is valid for absorption of neutrons in all nuclei concerned; and, therefore, not wholly true for uranium, which shows a pronounced resonance capture of neutrons of about 25 volts⁶. A certain proportion of neutrons entering the solution is bound to come within this resonance band and to be absorbed by resonance; therefore, it will never reach the thermal state. This proportion depends on the width of the resonance band and on the concentration

c_U ; its value in our system of symbols is equal to A_r/A_{tot} and was numerically determined by an experiment reported elsewhere⁵. 中文

文

Putting all numerical values in the formula (2) (with 10^{-24} cm.² as the unit of cross-section), that is: $\Delta S/S = 0.05 \pm 0.01$; $A_{tot} = 36 \pm 3$; $A_f = 1.6 \times 2 = 3.2$; $\Delta A_{tot} = 8.7 \pm 1.4$ decomposable into $\Delta A_H = 1.2 \pm 0.1$, $A_{ct} = 1.6 \times (1.3 \pm 0.45) = 2.1 \pm 0.7$, $A_r = 6.4 \pm 1.1$ and $A_f = 3.2$, we find:

$$\nu = 3.5 \pm 0.7.$$

中文

We were not able to allow for an error in A_f , since the value of σ_f given by Anderson *et al.* contains no indication of probable error. Any error in σ_f will affect $\nu - 1$ in an inversely proportional way; in any case ν will remain greater than 1. 中文

The interest of the phenomenon discussed here as a means of producing a chain of nuclear reactions was already mentioned in our previous letter. Some further conclusions can now be drawn from the results reported here. Let us imagine a medium containing only uranium and nuclei the total neutron absorption of which, as compared to that of uranium, may be neglected (containing, for example, only some hydrogen for slowing down purposes). In such a

medium, if $\frac{A_f}{A_{tot}} \cdot \nu > 1$ (A_{tot} includes now only uranium terms), the fission chain will perpetuate itself and break up only after reaching the walls limiting the medium. Our experimental results show that

this condition will most probably be satisfied (the quantity $\frac{A_f}{A_{tot}} \cdot \nu - 1$, though positive, will be, however, small), especially if one keeps in view that the term A_r , because of the self-reversal of the resonance absorption line, increases much more slowly than the other uranium terms when the uranium content of the medium is increased. 中文

H.von Halban, jun., F. Joliot and L. Kowarski: Laboratoire de Chimie Nucléaire, College de France, Paris, April 7.

References:

1. von Halban, jun., H., Joliot, F., Kowarski, L., *Nature*, **143**, 470 (1939).
2. Dodé, M., von Halban, jun., H., Joliot, F., Kowarski, L., *C.R.*, **208**, 995 (1939).
3. Roberts, R., Meyer, R., Wang, P., *Phys. Rev.*, **55**, 510 (1939).
4. Anderson, H., Booth, E., Dunning, J., Fermi, E., Glasoe, G., Slack, F., *Phys. Rev.*, **55**, 511 (1939).
5. von Halban, jun., H., Kowarski, L., Savitch, P., *C.R.* (in the Press).
6. Meither, L., Hahn, O., Strassmann, F., *Z. Phys.*, **106**, 249 (1937).

铀核裂变时释放的中子数量

冯·哈尔班等

实验已证实被中子轰击时铀核可以分裂为两个大核，并且裂变过程中会释放出次级中子。但是关于一个裂变事件中释放出多少中子，物理学家对此了解很少。但是这直接关系到自持裂变链式反应实现的可能性。物理学家汉斯·冯·哈尔班当时与费雷德里克·约里奥-居里及卢·科瓦尔斯基在巴黎一起工作，基于实验他对释放中子数进行了估测。答案是——平均3.5个——这意味着如果一个中子诱发一个裂变事件的可能性足够高，铀就可以发生链式反应。1940年德国入侵后，冯·哈尔班从法国逃亡到英国。 [英文](#)

最近的实验表明，慢中子轰击铀核引发核裂变可以释放出中子：次级中子在空间^[1]、能量^[2]、时间^[3]上的性质都与初级中子所拥有或者可能获得的性质不同。这些实验没有给出每次核分裂所产生的中子的平均数量；虽然这个数量 ν 可能非常小（小于1），但是实验测量仍然可以得出正的结果。 [英文](#)

现在我们可以给出 ν 值的一些信息。让我们仔细思考一下在包围着初级中子源^[1]的水溶液中减速的中子的密度分布曲线；曲线的面积 S 和 $Q\tau$ 成正比， Q 是每秒由中子源发射出的或在溶液中形成的中子数， τ 是中子被俘获之前在溶液中度过的平均时间。假设溶液中只有依照 $1/v$ 定律吸收中子的原子核（这个法则的唯一例外将在不久后处理）， τ 正比于 $1/\Sigma c_i \sigma_i$ ，其中 c_i 是吸收中子的原子核浓度（克原子每升）， σ_i 是所有速度为1的中子的俘获截面，指标 i 遍历溶液中原子核所致的各种中子吸收反应。用 A_i 代替 $c_i \sigma_i$ ，用 A_{tot} 代替 ΣA_i ，我们将得到：

$$\frac{\Delta S}{S} = \frac{\Delta Q}{Q} - \frac{\Delta A_{tot}}{A_{tot}} \quad (1)$$

上式忽略了所有包含诸如 $(\Delta Q)^2$ 、 $\Delta Q \cdot \Delta A_{tot}$ 等的高阶项。 [英文](#)

符号 Δ 代表我们在以前实验所使用的两种溶液（硝酸双氧铀和硝酸铵）中观察到的差值^[1]。在 A_{tot} 引入使 A_{tot} 定义不明确的因素之前， ΔA_{tot} 可以忽略不计，这（硝酸双氧铀对硝酸铵的值）在数值上并不重要，并且可以采用算数平均值 $(A_{tot}(\text{铵}) + \Delta A_{tot})/2$ 来进行简化。 [英文](#)

在 ΔA_{tot} 这个量中，铀原子核由代表不同中子俘获模式的分离项所描述（如下）；设 A_f 为引发裂变的俘获项。每个中子都有 A_f/A_{tot} 的引起裂变的概率，而且因为一次单独的裂变过程平均释放 ν 个中子，这样产生的中子总数 $\Delta Q = Q \cdot \frac{A_f}{A_{tot}} \cdot \nu$ ，则式（1）可以写成如下形式：

$$\nu = \frac{\Delta S}{S} \cdot \frac{A_{tot}}{A_f} + \frac{\Delta A_{tot}}{A_f} \quad (2)$$

[英文](#)

让我们估算一下用上式来计算 ν 所必需的量。面积变化量 $\Delta S/S$ 可以从我们以前文章的图中得知，其误差小于 20%（误差是由插值和外推的不确定性造成；为了便于外推，我们在曲线 $r = 29$ 厘米处增加了一个实验点）。利用已知的浓度和俘获截面（氢、氮和氧），可以很容易地计算出铵溶液中的 A_{tot} 值。 A_f 等于 c_U （在我们实验中值是 1.6）乘以安德森等人^[4]在近期文章中给出的 σ_f 值。 ΔA_{tot} 中包含了一个表示两种溶液中关于氢含量微小差异的项，以及三个与铀相关的项，即前面已经讨论过的裂变项 A_f ，可以用最近得到的 σ_{ct} 值来计算的热俘获项 A_{ct} ^[5]，还有共振俘获项 A_r ，最后这一项需要一些解释。 [英文](#)

我们合理地假设：所有进入溶液的中子，几乎全部寿命都处于热态，并且在这个态被吸收。只要保证所涉及的原子核对中子的吸收满足 $1/\nu$ 定律，这个假设就是成立的；然而，对于 25 电子伏的中子有显著中子共振俘获的铀^[6]，这个假设并不完全成立。因为以一定比例进入溶液的中子会被束缚在这种共振带中，并被共振吸收；因此，它们就不会到达热态。这个比例依赖于共振带宽和浓度 c_U ；在我们的符号系统中，其数值等于 A_r/A_{tot} ，我们已经有实验确定了它的数值并已在别处发表^[5]。

[英文](#)

把上述所有的数值都代入公式(2)(以 10^{-24} 平方厘米作为截面的单位),即: $\Delta S/S = 0.05 \pm 0.01$; $A_{tot} = 36 \pm 3$; $A_f = 1.6 \times 2 = 3.2$; $\Delta A_{tot} = 8.7 \pm 1.4$, 可以分解为 $\Delta A_H = 1.2 \pm 0.1$; $A_{ct} = 1.6 \times (1.3 \pm 0.45) = 2.1 \pm 0.7$, $A_r = 6.4 \pm 1.1$, $A_f = 3.2$, 我们得到:

$$v = 3.5 \pm 0.7$$

英文

我们无法推算 A_f 的误差,因为安德森等人给出的 σ_f 值并不包含任何可能的误差值。 σ_f 中的任何误差都会对 $v-1$ 产生一个反比例的影响;但无论怎样, v 都会大于1。 英文

本文讨论的现象可以作为一种产生链式核反应的方法,我们在以前的文章中已经提到过它的重要性。这里报道的结果可以得到一些更进一步的结论。设想一种介质中只含有铀和一些与铀相比对中子的吸收可以忽略不计的原子核(比如,只含有一些用于减速的氢)。在这种介质

中,如果 $\frac{A_f}{A_{tot}} \cdot v > 1$ (A_{tot} 此处只含有铀的项),链式裂变反应将一直继续下去,直到到达介质的边界为止。我们的实验结果表明,这种条件非

常有可能实现($\frac{A_f}{A_{tot}} \cdot v - 1$ 的值虽然为正,但是会非常小),特别是考虑到当介质中的铀含量增加时,由于共振吸收线的自蚀, A_r 要比铀的其他项增加得缓慢得多。 英文

(王静 翻译;夏海鸿 审稿)

Control of the Chain Reaction Involved in Fission of the Uranium Nucleus

F. Adler and H. von Halban, jun.

Because roughly 3.5 neutrons are typically released in a uranium fission event, physicists now understood that chain reactions were probably possible. There is thus a considerable danger, as Felix Adler and Hans von Halban here note, that a sample of uranium might explode. But they also suggest a means for controlling such reactions. Into a system of highly concentrated uranium one might insert materials known to absorb neutrons efficiently, such as cadmium. In so doing, the number of further fission events triggered by one such event could be tuned close to 1, so that the reaction would grow only slowly. This suggestion ultimately pointed the way to the “moderator rods” used to control reactions in modern nuclear reactors. [中文](#)

IT has recently been shown that the number¹ of neutrons liberated² in the nuclear fission of a uranium nucleus is sufficiently high to make the realization of a self-perpetuating reaction chain seem possible. The danger that a system containing uranium in high concentration might explode, once the chain is started, is considerable. It is therefore useful to point out a mechanism which gives the possibility of controlling the development of such a chain. [中文](#)

We form an expression which is characteristic for the behaviour of the chain:

$$\nu'' = \frac{A_f}{A} \nu (1 - \alpha) \quad (1)$$

A_f being the product of the cross-section for nuclear fission for a thermal neutron of the uranium nucleus with the concentration of the uranium; A_i the product of the absorption cross-section for thermal neutrons of the nucleus of kind i multiplied with its concentration; A the sum of all A_i 's, which is to be taken over all kinds of nuclei present in the solution; ν is the average number of neutrons liberated in one fission, α the average probability for a neutron to diffuse out of the system before being absorbed. [中文](#)

The energy liberated by the chain will be

$$E = NF, \quad (2)$$

F being the energy liberated in one fission and N the number of fissions produced by the chain. We have

$$N = \nu'' + \nu''^2 + \nu''^3 + \dots \quad (3)$$

[中文](#)

The chain gives thus a quantity of energy, which is increasing rapidly with time, if ν'' is greater than 1. Let us consider the case of a chain which is due to fission produced by thermal neutrons; that is, a chain propagating itself in a system containing sufficient hydrogen for the slowing down of the neutrons. [中文](#)

If the cross-sections for capture or fission of all nuclei present follow the $1/\nu$ law, ν'' will not depend on the velocity of the neutrons and therefore not on the temperature of the system (since α will in practice

be small and since it depends in the first place on the distance necessary for slowing down the neutron; the temperature has, of course, an effect, although it will be very small). 中文

Let us, however, introduce an absorbent, such as cadmium, the cross-section of which does not depend on the neutron energy in the thermal region. We will have, instead of (1),

$$\nu'' = \frac{A_f}{A' + A_c}(1 - \alpha), \quad (4)$$

where A' is the sum of all A_i 's following the $1/v$ law and A_c is a constant, the term due to the newly added absorbent. ν'' will now decrease with increasing temperature. At a temperature, which will be characteristic for the composition and the geometrical constants of the system, ν'' will become smaller than unity and the system will stabilize itself somewhere near this temperature; the equilibrium being determined by the fact that the amount of energy given out per unit of time by the system (in the form of heat and nuclear radiation) is equal to the energy produced by the system. Similar questions have been discussed by F. Perrin³. 中文

Added in proof: In the case of a chain propagating itself by thermal neutrons, the time necessary for the slowing down and for the absorption of a neutron, that is, its mean life, is of the order of 10^{-4} sec. If one makes ν'' as small as 1,007, it needs 100 times the mean life of a neutron or about 10^{-2} sec. to double the number of neutrons, and with that the energy liberated per unit of time. It is therefore possible to control the development of the chain by a periodical interaction of absorbers which break up the chains by entering the system. 中文

(143, 793; 1939)

References:

1. von Halban, jun., H., Joliot, F., and Kowarski, L., *Nature*, **143**, 470 (1939).
2. von Halban, jun., H., Joliot, F., and Kowarski, L., *Nature*, **143**, 680 (1939). Roberts, R., Meyer, R., and Wang, P., *Phys. Rev.*, **55**, 510 (1939). Haenny, C., and Rosenberg, A., *C.R.*, **208**, 898 (1939). Szilard and Zinn (private communication). Huber and Buldinger (private communication).
3. Perrin, F., *C.R.*, in the Press.

铀核裂变中链式反应的控制

阿德勒，冯·哈尔班

由于平均每个铀核裂变事件中大约释放3.5个中子，物理学家此时已明白链式反应是可以发生的。正如费利克斯·阿德勒和汉斯·冯·哈尔班在本文中所说的，铀样品可能会爆炸，并且会产生相当大的危险。不过他们也提出了一个控制这种反应的方法。对于包含高浓缩铀的系统，人们可以往里面注入已知的可以有效吸收中子的材料，例如镉。通过这种做法，可以将一个裂变事例触发的次级裂变的数目控制在1左右，因此整个反应可以缓慢地进行。这个建议从根本上提供了现代核反应堆中反应的“控制棒”的制作途径。 [英文](#)

最近实验表明，一个铀核在核裂变时释放^[2]出的中子的数目^[1]似乎高到足以使自持反应链的实现成为可能。一个含有高浓度铀的体系一旦开始链式反应就可能会爆炸，这种危险是不容忽视的。因此，提出一种可能能够控制这种链式反应发展的机制将是有益的。 [英文](#)

我们构建了一个描述链式反应行为的特征表达式：

$$\nu'' = \frac{A_f}{A} \nu (1 - \alpha) \quad (1)$$

其中 A_f 是热中子铀核裂变截面与铀浓度的乘积； A_i 是*i*类核的热中子吸收截面与该类核的浓度的乘积； A 是所有 A_i 之和，此求和遍及存在于溶液中的所有类型的核； ν 是一次裂变中释放出中子的平均数目， α 是一个中子在被吸收前扩散到体系外的平均概率。 [英文](#)

链式反应释放的能量为：

$$E = NF$$

其中 F 是一次裂变释放出的能量， N 是由链式反应所产生的裂变数目。我们有

$$N = \nu'' + \nu''^2 + \nu''^3 + \dots \quad (3)$$

英文

于是链式反应给出了能量的值，当 ν'' 大于1时，该值随时间的增加快速增加。让我们来考虑由热中子引发的裂变所导致的一个链式反应；即一条在含有足够用来慢化中子的氢的体系中的自持增殖链。

英文

如果所有核的俘获或裂变截面都遵循 $1/v$ 定律，那么 ν'' 就不会依赖于中子的速度，因此也就不依赖于系统的温度（因为 α 实际上会是很小的，而且它首先取决于慢化中子所必需的距离；当然，温度也会产生一定的影响，尽管这种影响很小）。

英文

不过，我们可以引入一种吸收剂，比如镉，它的截面不依赖于热区的中子的能量。我们将用下面的式子来代替式（1）：

$$\nu'' = \frac{A_f}{A' + A_c}(1 - \alpha) \quad (4)$$

其中 A' 是所有遵循 $1/v$ 定律的 A_i 的和，而 A_c 是一个常数，它取决于新加入的吸收剂。此时的 ν'' 将会随着温度的增加而减小。在系统的组成和几何常数的特征温度下， ν'' 会变得比1还小，而系统则会在该温度附近的某个温度下达到自稳定；平衡是由下面的事实所决定的，即单位时间内系统释放出的能量大小（以热或者核辐射的形式）等于系统产生的能量。佩兰曾经讨论过类似的问题^[3]。

英文

附加说明：在热中子所导致的自持增殖链的情况中，对中子慢化和吸收所需要的时间，即中子的平均寿命，为 10^{-4} 秒的数量级。如果使 ν'' 小到1.007，就需要100倍于中子平均寿命或者说大约 10^{-2} 秒的时间来使中子数量加倍，同时单位时间释放的能量也随之翻倍。于是，有可能通过利用吸收剂周期性的相互作用（它会进入系统破坏链式反应）来控制链式反应的发展。

英文

(王耀杨 翻译；张焕乔 审稿)

Emission of Neutrons Accompanying the Fission of Uranium Nuclei

J. Rotblat

The Polish physicist Joseph Rotblat here supplies further evidence on the release of neutrons in the fissioning of uranium nuclei, indirect evidence for which had already been reported. Using a new technique, he suggests that the number of secondary neutrons produced in a fission event might be as high as six. Rotblat went on to work on the Manhattan Project which led to the atomic bomb, but after the war became a fierce critic of nuclear weapons and worked tirelessly on international arms control. In 1957, with the philosopher Bertrand Russell, Rotblat founded the highly influential Pugwash Conferences, which bring together scientists and public figures in an effort to reduce the proliferation of nuclear weapons. [中文](#)

THE experiments of Halban, Joliot, and Kowarski described in *Nature*¹ give an indirect proof of the neutron multiplication accompanying the fission of uranium nuclei after neutron capture. It can be deduced from these experiments that the additional neutrons are, on the average, faster than the photo-neutrons from radium C-beryllium used as active primary radiation. This conclusion is confirmed in a subsequent note² by the same authors in which they

find that the neutrons contributed by uranium are able to produce the endo-energetic reaction $S(n, p)P$. 中文

I have made some experiments on the same problem by a different method. Any increase of neutron effects observed when neutrons are allowed to pass through a given medium may be due: (a) to the inelastic scattering of neutrons, (b) to the reaction $(n, 2n)$ or, exceptionally $(n, 3n)$; (c) to an unknown cause, as in the case of uranium to the fission of its nuclei. In the experiments of Halban, Joliot and Kowarski, effects (a) and (b) are excluded owing to the integrating method adopted and to the low energy of the primary neutrons. But if these effects are present, it is possible to estimate their importance relatively to effect (c) by comparing uranium with substances in which only effect (a) or only (a) and (b) are possible. I have used aluminium and copper as comparison substances of the first and of the second type respectively. 中文

A radon plus beryllium source was placed in the cylindrical axial hole of a cylinder of aluminium, of 2.2 cm. diameter and 5 cm. height, or, alternatively, of a cylindrical double-walled vessel of identical dimensions filled with uranium oxide (U_3O_8) or copper oxide. The mass of aluminium was 40 gm., of uranium oxide 49 gm. and of copper oxide 42 gm., and the thickness of walls could be neglected. The number of absorbing or scattering uranium nuclei was therefore 9.2 times smaller than the corresponding number of aluminium nuclei and 3.3 times smaller than the number of copper nuclei. One would expect, therefore, that the effect (a) due to aluminium, and effects (a) and (b) due to copper would be at least of the same importance and probably larger than the same effects due to uranium. The number and quality of neutrons issuing from these substances were compared by measuring the activation of a silver foil surrounding the cylinders in two cases: first, when no appreciable scattering of neutrons took place outside the cylinders, and secondly, when the neutrons were

scattered back by a cylindrical sheet of paraffin wax of 6 mm. thickness. The results are given below, the figures being the total numbers of counts of a Geiger-Müller counter in corresponding series.

中文

	Aluminium	Uranium	Increase (%)	Copper	Uranium	Increase (%)
No paraffin	9,089	9,325	2.6	4,810	4,869	1.2
With paraffin	10,285	10,775	4.8	10,049	10,292	2.4

中文

It can be inferred from these data that uranium gives off, in fact, more neutrons than aluminium or copper. The increase is larger relatively to aluminium than to copper, which must be attributed to the reaction ($n,2n$) occurring in this last element. In both cases, the increase is larger when the neutrons are slowed down by a small quantity of paraffin, which shows that the additional neutrons from uranium are, on the average, slower than the bulk of primary neutrons emitted by the source. As, from other evidence, they appear to be faster than the radium C-beryllium neutrons, we can estimate that their *average* energy must be of the order of 1 Mev.

中文

Owing to the small number of uranium nuclei acting as absorbers or scatterers, it seems very unlikely that the apparent excess of neutrons given off by these nuclei should be due to some trivial cause like the inelastic scattering or the reaction ($n,2n$). It probably represents the neutron shower' accompanying the fission of an activated uranium nucleus. Assuming the cross-section for this process produced by the neutrons from radon plus beryllium equal to 5×10^{-25} cm.², I calculate that the number of neutrons emitted in a single fission is equal to 6.

中文

(143, 852; 1939)

References:

1. *Nature*, **143**, 470 (1939).
2. *C.R.* **208**, 995 (1939).

伴随铀核裂变的中子发射

罗特布拉特

波兰物理学家约瑟夫·罗特布拉特在本文中提供了关于铀核裂变过程中中子释放的进一步证据，此前已经报道过相关的间接证据。他使用了一项新技术，并提出一个裂变事件中产生的次级中子数目可能高达6个。罗特布拉特持续从事研制原子弹的曼哈顿项目工作，但是战后他成了核武器的强烈批评者，并且坚持不懈地致力于国际核武器控制。1957年，罗特布拉特和哲学家伯特兰·罗素一起发起了具有极大影响力的帕格沃什会议，这次会议上科学家和社会名人一起努力以实现减少核武器的扩散。 [英文](#)

哈尔班、约里奥和科瓦尔斯基在《自然》中所描述的实验^[1]为在中子俘获之后伴随着铀核裂变的中子倍增提供了间接证据。从这些实验可以推知，一般来说，这些新产生的中子比来自作为放射性初级辐射的镭C-铍源的光中子更快。这一结论在这几位作者随后的一篇文章^[2]中得到证实，他们发现由铀贡献的中子能够产生吸能反应 $S(n, p)P$ 。 [英文](#)

我对同样的问题用不同方法做了一些实验。在令中子通过一种给定介质的实验中，所观察到的中子效应的任何增长都可能是由于以下原因造成的：（a）中子的非弹性散射；（b） $(n, 2n)$ 反应，个别时候是 $(n, 3n)$ 反应；（c）未知原因，就像在铀核裂变的情况中那样。在哈尔班、约里奥和科瓦尔斯基的实验中，由于集成方法的采用和初级中子的能量较低，故可以排除效应（a）和（b）。但是如果这些效应存在的话，就有可能通过将铀与只可能有（a）效应或只有（a）和（b）效应的物质进行比较，进而估计出它们相对于效应（c）的重要性。我曾经使用铝和铜分别作为第一类和第二类对比物质。 [英文](#)

把氡-铍放射源置于一个铝质圆柱体（直径为2.2厘米，高为5.0厘米

米) 轴向的孔中, 或者, 也可以采用同样尺寸的装填有氧化铀 (U_3O_8) 或氧化铜的圆柱形双层壁容器。铝的质量为40克, 氧化铀质量为49克, 氧化铜质量为42克, 器壁厚度是可忽略的。结果吸收或散射的铀核数目是相应的铝核数目的1/9.2, 是铜核数目的1/3.3。由此我们预期, 铝产生的效应 (a) 与铜产生的效应 (a) 和 (b) 至少是同样重要的, 甚至可能比铀产生的同种效应更大。我们将这些物质所发出的中子的数目和性质进行比较, 比较的方法是分别在下述两种情况下测量包裹在圆柱体周围的银箔的放射性: 第一种情况是在圆柱体外部没有发生明显的中子散射时, 第二种情况是中子经6毫米厚的圆柱形石蜡层散射而返回时。下面数据列出了该实验的结果, 数字表示用盖革-米勒计数器在相应的序列中得到的总计数。

[英文](#)

	铝	铀	增量 (%)	铜	铀	增量 (%)
无石蜡	9,089	9,325	2.6	4,810	4,869	1.2
有石蜡	10,285	10,775	4.8	10,049	10,292	2.4

[英文](#)

根据这些数据可以推测, 事实上铀比铝或者铜发射出更多的中子。相对于铝的增量比相对于铜的增量要大, 这必定是因为后一种元素中发生了 ($n, 2n$) 反应。在铝和铜两种情况中, 当中子被少量石蜡慢化时这种增量是比较大的, 这表明从铀所产生的的新的中子平均来说比放射源发射出的大量初级中子慢。由于在其他的证据中, 它们似乎比镭C-铍中子快, 因此我们可以估算出它们的平均能量必定具有1兆电子伏的数量级。

[英文](#)

由于作为吸收体或散射体的铀核数目较小, 所以由这些核发射出的中子的明显过剩似乎不可能归结为某些细微的原因, 比如非弹性散射或 ($n, 2n$) 反应。它可能代表了伴随着一个放射性铀核的裂变而产生的中子簇射。假定由氡-铍源的中子产生这个过程的截面等于 5×10^{-25} 平方厘米, 我计算出单独一次裂变发射出的中子数等于6。

[英文](#)

(王耀杨 翻译; 张焕乔 审稿)

Fission of Heavy Nuclei: a New Type of Nuclear Disintegration

N. Feather

Physicist Norman Feather offers a review of advances in the understanding of nuclear fission reactions, and the possibility of a controlled chain reaction. In retrospect, he notes, the first evidence for fission in uranium nuclei came in experiments by Enrico Fermi and colleagues in 1934, though five years passed before the physics could be clarified. It was now clear that each such fission gave off several neutrons on average, and may well suffice to drive a sustained chain reaction. However, experiments also showed that slow “thermal” neutrons are most effective in stimulating fission events. No experiments on chain reactions had at that point been carried out, however. [中文](#)

THE first indication that the transmutation of heavy nuclei could be effected in a laboratory experiment was obtained by Fermi in March 1934. Curie and Joliot had just discovered that short-lived radioactive species are produced as the result of α -particle bombardment of certain light elements, and Fermi, accepting the appearance of such “induced” radioactivity as proof of transmutation, very soon showed that the nuclei of almost all elements, even those of highest atomic weight, undergo transformation when neutrons are used. From his early experiments Fermi concluded that in general the neutron is simply captured by the nucleus, and he went on to show that this

process of capture is usually more efficient—and sometimes very much more efficient—when the neutron is moving with a small (“thermal”) velocity, before the collision, than when its energy is large. Eventually he found that negative electrons were emitted in the disintegration of the radioactive products obtained in all these capture transformations, and thus the final result of the combined process of neutron capture and β disintegration was in every case shown to be the production of a nucleus having both mass and charge numbers greater by one unit than the mass and charge numbers of the nucleus bombarded. [中文](#)

In June 1934¹, Fermi and his collaborators obtained negative electron activities from thorium and uranium under neutron bombardment, and they quite naturally supposed, on the basis of their previous investigations, that in the latter case a nuclear species of atomic number $Z = 93$ must remain after disintegration of the unstable product first formed. Further examination showed that not one but several distinct radioelements were produced as a result of the bombardment of uranium, and rough chemical tests proved that one of these, at least (half-value period $\tau = 13$ minutes), was not attributable to an element of atomic number $Z = 92, 91, 90, 89, 88, 83$ or 82 . It seemed quite clear, then, that after the uranium nucleus had captured a neutron, not less than two β transformations followed, and consequently that a new element, for which Z was not less than 94 , was ultimately produced. These conclusions at once gave rise to much argument amongst chemists as to what the chief chemical properties of these hypothetical transuranic elements might be, but a great deal of careful research in many physical laboratories throughout the world only served to strengthen the assumption that, apart from any preconceived ideas about chemical behaviour, such elements were certainly formed when uranium was bombarded by neutrons. [中文](#)

By May 1937, Meitner, Hahn and Strassmann² had recognized the existence of nine separate species arising from this transformation, and had suggested genetic relations between them which supposed that every element of atomic number between (and including) 92 and 97 was represented, either as intermediate or end product of a series. They identified three of these nine products ($\tau = 10$ sec., 40 sec., 23 min.) as unstable isotopes of uranium, and the remainder, which could all be obtained by precipitation with platinum as sulphide in acid solution, as the transuranic elements already mentioned. The scheme presented certain difficulties, it was admitted, (no evidence for the final return of the unstable nucleus within the ordinary range, Z less than 93, could be found, and awkward questions concerning isomeric forms were raised in an acute form) but it was the best that could be done. [中文](#)

Then, in October 1937, Curie and Savitch³ discovered a tenth activity of about $3\frac{1}{2}$ hours period, and at once proceeded to investigate the chemical nature of the element to which it belonged. They showed that this radioelement did not separate with the platinum precipitate and soon discovered that it bore a close resemblance to lanthanum in chemical behaviour. At first the most plausible suggestion appeared to be that the new species was an isotope of actinium ($Z = 89$). Then two very disturbing facts were encountered. First, a body of the same period and almost identical properties was among the active products formed in the disintegration of thorium by neutrons, and, secondly, it was found possible to separate actinium almost completely from the new body by a lanthanum fractionation. In September 1938, Curie and Savitch⁴ wrote, "On the whole, the properties of R 3.5 h. are those of lanthanum, from which it appears that until now it has not been separated". [中文](#)

The work of Curie and Savitch immediately prompted a further search for activities belonging to elements of atomic number less than 92

produced in the uranium transformation, and, as a result, Hahn and Strassmann⁵ discovered two other lanthanum-like and three barium-like products. These workers believed that they had demonstrated the production of each of the former species from one of the latter, but at that time they still inclined to the view that actinium and radium isotopes were really in question. However, in January of this year, they reported⁶ that fractionation of the new bodies with mesothorium and barium (or lanthanum) invariably concentrated the neutron-produced activity with the lighter carrier and resulted in a complete separation of mesothorium 1 (radium), or mesothorium 2 (actinium). The conclusion now appeared inescapable that active isotopes of barium and lanthanum were among the products of the bombardment of uranium with neutrons. [中文](#)

At this stage, Meitner and Frisch⁷ discussed the problem on the Bohr theory of heavy nuclei, making particular use of the essentially classical “water-drop model” of the highly condensed system of particles of which such a nucleus is constituted. They concluded, “It seems therefore possible that the uranium nucleus has only small stability of form, and may, after neutron capture, divide itself into two nuclei of roughly equal size. ... These two nuclei ... should gain a total kinetic energy of c. 200 Mev. ... This amount of energy may actually be expected to be available from the difference in packing fraction between uranium and the elements in the middle of the periodic system”. Then Frisch⁸ obtained direct evidence for the projection of fission fragments with approximately the energy predicted, being able to detect the production of large bursts of ionization in a uranium-lined ionization chamber which was irradiated by neutrons. Similar results were obtained when thorium was substituted for uranium in the chamber, and it was concluded that some of the activities previously ascribed to isotopes of radium and actinium, in this case also resulted from fission of the nucleus under neutron bombardment.

The investigations begun by Meitner and Frisch were rapidly followed by many others in physical laboratories both in Europe and in the United States: the confirmation of the findings of Curie and Savitch by Hahn and Strassmann had indicated quite clearly to many workers that something new was involved. In Paris, in Berkeley, in Washington, New York and Baltimore, direct proof of the fission of uranium and thorium was obtained within the space of a few days. Now, some three and a half months after the original announcement, so much has been published that rigorous selection is necessary in any report on the subject. For the remainder of this survey, therefore, only the most interesting features of the new phenomenon can possibly be included. [中文](#)

Perhaps the first such feature concerns the radioelements of the platinum precipitate, of which the previously supposed transuranic nature was now in question. Before the fission process was discovered, both in Berkeley and in Cambridge projects had already been formed of investigating these elements for natural X-radiations, in the hope of being able to deduce the atomic number from the energy of the radiations (natural *L*-radiations) as determined by the method of critical absorption. This problem became much simpler once the presence of medium-heavy elements was suspected, since *K*-radiations could be looked for, instead of the more complex radiations of the *L*-series. Almost at once, Abelson⁹ and Feather and Bretscher¹⁰ found evidence for the natural *K*-radiations of iodine from the long-lived activities of the platinum precipitate, and, guided by this observation, were able to identify chemically as tellurium and iodine two products previously described as eka-iridium and eka-platinum, respectively. Then several workers found other of the so-called transuranic activities in the products collected by recoil from bombarded uranium. Observations concerning the rates of decay of these recoil activities¹¹—and the results of chemical tests¹²—left little doubt that almost all the previous assignments had been seriously in error. At the present

time, one might justly say that it cannot definitely be maintained, concerning any of the activities separable from uranium, that it does not arise in a process of fission of the uranium nucleus. 中文

There is, however, one important activity, of 23 minutes half-value period, which is not separable from uranium and for which, in consequence, the fission process cannot be assumed to be responsible. This non-separable activity arises in a process of resonance capture of neutrons of about 25 ev. energy, and the fact that negative electrons are involved must clearly indicate that a species for which $Z = 93$ is formed as the result of the disintegration. Yet, in spite of much careful investigation, no radioactivity of any kind has been discovered which is unquestionably due to the transformation of this species. Furthermore, in respect of the parent species (the uranium isotope for which $\tau = 23$ min.), this is clearly a quasi-stable modification of the body which undergoes fission in the majority of cases, and Meitner and Frisch and Bohr¹³ have discussed this aspect of the phenomenon. They have pointed out that there is nothing intrinsically incomprehensible in the occurrence of resonance capture (emission of γ -radiation) rather than fission in certain circumstances. In any event, division of the nucleus into two fragments must be preceded by the concentration of the available energy in a type of nuclear motion of large deformation, and this concentration may be very unlikely if the original state of the system, after capture of the neutron, is one of considerable symmetry. Or if, as Bohr has assumed, the effect of thermal neutrons in producing fission in the case of uranium (such neutrons are quite ineffective when thorium is bombarded) is ascribed to capture by the rare isotope ^{235}U , and the resonance effect and the fission process due to fast neutrons are ascribed to ^{238}U , it may even be that, at the resonance energy, the compound nucleus is not formed with sufficient energy of excitation for the neutralization of the small stability of form which it naturally possesses. As regards the whole of this question, more definite conclusions must clearly await further

experiments: Joliot¹⁴ has reported a variation in the relative proportions of the different fission products as the energy of the neutrons is altered—and this might be held to favour the suggestions of Bohr—but Bjerger, Brostrøm and Koch¹⁵ have failed to establish any difference in the decay of the products obtained with high-energy neutrons and thermal neutrons, respectively. 中文

Hitherto, the process of fission has been spoken of without any precise statement regarding the nature of the fragments which result from the primary act of division of the nucleus, and in fact very little exact knowledge is as yet available on this point. Determinations of the range of the fission products provide some information. In the first place, they indicate that (with uranium and fast neutrons) the process occupies less than 5×10^{-13} sec. from the time of capture of the neutron (the forwards range is slightly greater than the backwards range, showing that very little of its original momentum is lost before the compound nucleus divides¹⁶), and, secondly, they appear to favour a very small number of competing primary processes, rather than a large number of possibilities¹⁷. On the other hand, chemical investigation reveals such a wealth of active products¹⁸ (with atomic numbers lying between 35 (Br) and 57 (La), if not more widely distributed) that some adequate explanation of their complexity must certainly be found. It would appear that the discovery that very frequently neutrons are emitted almost instantaneously by the original products of fission¹⁹ already provides a basis for such explanation (nuclei, first formed, presumably, in states of high excitation, emit either neutrons or quanta of radiation in passing to longer-lived states). Also, even after these states have decayed with β -emission, experiment shows that occasionally product nuclei result, still with sufficient energy of excitation for the “evaporation” of neutrons to be a possible alternative to radiative transitions leading to more stable states. In this connexion, Roberts, Meyer, and Wang²⁰ and Booth, Dunning and Slack²¹ have reported delayed neutron periods of about

12 sec. and 45 sec., when uranium is bombarded, whilst a similar feature has also been established in the case of thorium. 中文

The frequency of the neutron-evaporation process accompanying fission, and the energies of the neutrons so produced, have been studied by many workers, but so far most exhaustively by Joliot²² and his colleagues, and by Fermi²³ and others in New York. The general result appears to be that, for each process of fission with uranium, at least two neutrons, having a mean energy of the order of 10^6 ev., eventually evaporate from the residual fragments. Since neutrons of less than this energy are still capable of producing fission on their own account (probably in ^{235}U , as already suggested), the possibility of a cumulative process of exothermic disintegration has to be considered. Clearly, if the probability of removal of neutrons in processes other than those which result in fission is sufficiently reduced, the latter process must eventually build up in any solid substance containing uranium. Direct experiments on this aspect of the matter have not yet been reported in the scientific literature, but at this stage it may be pointed out that, even in pure uranium, it is well known that a non-fission capture process takes place (*v. sup.*), whilst the unlimited generation of energy in the solid material would ultimately increase the energy of the “thermal” neutrons until their efficiency as agents for fission was greatly reduced. Already several attempts have been made²⁴ to calculate the course of the phenomenon using existing data, but the assumptions upon which they have been based have generally been so severely idealized that no confidence in numerical values is at present likely to result. 中文

(143, 877-879; 1939)

N. Feather: Cavendish Laboratory, Cambridge.

References:

1. *Nature*, **133**, 898 (1934).

2. *Z. Phys.*, **108**, 249 (1937).
3. *J. Phys.*, **8**, 385 (1937).
4. *J. Phys.*, **9**, 355 (1938).
5. *Naturwiss.*, **26**, 755 (1938).
6. *Naturwiss.*, **27**, 11 (1939).
7. *Nature*, **143**, 239 (1939).
8. *Nature*, **143**, 276 (1939).
9. *Phys. Rev.*, **55**, 418 (1939).
10. *Nature*, **143**, 516 (1939).
11. Meitner and Frisch, *Nature*, **143**, 471 (1939). Glasoe and Steigman *Bull. Amer. Phys. Soc.*, (2), **14**, 20 (1939).
12. Bretscher and Cook, *Nature*, **143**, 559 (1939).
13. *Phys. Rev.*, **55**, 418 (1939).
14. *J. Phys.*, **10**, 159 (1939).
15. *Nature*, **143**, 794 (1939).
16. Feather, *Nature*, **143**, 597 (1939).
17. McMillan, *Phys. Rev.*, **55**, 510 (1939).
18. Heyn, Aten and Bakker, *Nature*, **143**, 516 (1939). Abelson, *phys. Rev.*, **55**, 670 (1939).
19. v. Halban, Joliot and Kowarski, *Nature*, **143**, 470 (1939).
20. *Phys. Rev.*, **55**, 510 (1939).
21. *Bull. Amer. Phys. Soc.*, (2), **14**, 19 (1939).
22. v. Halban, Joliot and Kowarski, *Nature*, **143**, 680 (1939). Dodé, v. Halban, Joliot and Kowarski, *C.R.*, **208**, 995 (1939).
23. Anderson, Fermi and Hanstein, *Phys. Rev.*, **55**, 797 (1939). Szilard and Zinn, *Phys. Rev.*, **55**, 799 (1939).
24. For example, Perrin, *C.R.*, **208**, 1394 (1939).

重核裂变：一种新型的核蜕变

费瑟

物理学家诺曼·费瑟根据他对核裂变以及可控链式反应的可能性的理解写了一篇综述性文章。他指出实验上首次观察到铀核裂变的证据是在1934年由恩里科·费米及其同事发现的，然而5年后裂变的物理原理才被阐释。现在人们知道每个这样的裂变反应平均释放几个中子，并且有可能驱动持续的链式反应。但实验也表明慢的“热”中子对于激发裂变是非常有效的。不过关于这一点，还没有链式反应实验予以证实。 [英文](#)

在实验室所进行的实验中，费米于1934年3月首次发现影响重核嬗变的迹象。居里和约里奥刚刚发现 α 粒子轰击某些轻元素时会产生短寿命的放射性核素，费米便认识到这种“诱发的”放射性的出现可以作为嬗变的证据，并且很快指出，几乎所有元素的核——即使是那些具有最大原子量的核——在用中子轰击时都会发生转变。费米根据自己的早期实验推断，中子通常只是被核俘获，他接着指出，当撞击前的中子以慢的（“热”）速度运动时，这个俘获过程一般会比它具有高能量时更为有效——而且有时会高效很多。最后他发现，在所有这些俘获转变中生成的放射性产物，它们的分裂都会释放出负电子。因此，在任何情况下，兼有中子俘获与 β 蜕变的组合过程的最终结果都显示出，生成的核的质量和电荷数都比被轰击核大一个单位。 [英文](#)

1934年6月^[1]，费米及其合作者通过用中子轰击钍和铀，得到了负电子放射性。于是，基于之前的研究，他们很自然地认为，在后一情况中，最初形成的不稳定产物蜕变之后一定会有一种原子序数 $Z=93$ 的核素保存下来。进一步的检测表明，轰击铀的结果不是生成了一种放射性元素，而是生成了几种截然不同的放射性元素，而粗略的化学检验证

明，其中至少有一种（半衰期 $\tau=13$ 分钟）不能归结为原子序数 $Z=92$ 、91、90、89、88、83或82的元素。于是，看起来非常明确，铀核在俘获了一个中子后至少会接着发生两次 β 转变，因而最终会生成一种 Z 不小于94的新元素。这些结论立刻在化学家中间引起了很多争论，内容是关于这些假想的超铀元素可能具备的主要化学性质是什么的问题。然而除去任何预先的关于化学行为的想法，在全世界多所物理实验室中所进行的大量细致的研究却只能用来支持下面的假设，即这些元素确实是在中子轰击铀时形成的。 [英文](#)

到1937年5月时，迈特纳、哈恩和施特拉斯曼^[2]已经认识到存在着9种由这类转变所产生的独立核素，并且提出了它们之间的亲缘关系，这种关系假定原子序数介于（且包括）92和97之间的每一种元素不是作为某一序列的中间产物就是作为其最终产物而出现。他们鉴别出这9种产物中的3种（半衰期 $\tau=10$ 秒、40秒、23分钟）是铀的不稳定同位素，而其余的几种都可以通过在酸溶液中与铂以硫化物的形式沉淀而得到，它们被视为是前面提到的超铀元素。虽然这一方案存在着某些难点，但人们还是接受了，（没有能够找到最终收回的不稳定核处于 Z 小于93的常规范围内的证据，这就尖锐地提出了有关异构形式的棘手问题），而这也是当时所能做到的方案中最好的一个。 [英文](#)

然后，1937年10月，居里和萨维奇^[3]发现了半衰期为3.5小时的第10种放射性，并立即着手研究该放射性所属元素的化学本质。他们指出这种放射性元素不能用铂沉淀来分离，并且很快发现它的化学行为与镧极为相似。最初看来最有道理的观点似乎是，这一新核素是镧（ $Z=89$ ）的某种同位素。但是后来遇到两个令人极为困扰的事实。第一，在中子轰击所导致的钍的分裂中形成的放射性产物中，存在着某种具有相同周期和几乎同样性质的物质，第二，发现通过镧分级分离的方法，从这种新物质中有可能将镧几乎完全分离出来。1938年9月居里和萨维奇^[4]写到，“大体上讲，半衰期3.5小时就是镧的性质，而到目前为止，似乎仍不能把这种新元素与镧分离开来”。 [英文](#)

居里和萨维奇的工作直接促进了在铀转变过程中产生的原子序数小于92的元素的放射性的进一步研究。而其结果是，哈恩和施特拉斯曼^[5]发现了另外两种类镧产物和三类钡产物。这些研究者相信，他们已经

论证了所有类镭产物都是由类钡产物中的一种产生的，但是在那时，他们仍然倾向于这样的观点，即镭和钍的同位素有待研究。不过，今年1月他们报道了^[6]含有新钍和钡（或镭）的新物质的组分，总是可以通过较轻载体聚集由中子引起的放射性，从而导致新钍1（钍）或新钍2（镭）的完全分离。这时得到如下结论似乎是顺理成章的，即在铀经中子轰击所得产物之中存在着钡和镭的放射性同位素。 [英文](#)

在这个阶段，迈特纳和弗里施^[7]对玻尔的重核理论中存在的问题进行了讨论，尤其是应用了本质上经典的“液滴模型”来描述构成这种核的粒子所组成的高密度系统。他们得出结论，“由此看来，可能铀核只具有较低稳定性的形式，并且可能在俘获中子之后将自身分裂成两个大小基本相同的核。……这两个核……应该获得大约200兆电子伏的总动能。……根据铀和位于周期表中部的元素之间聚集率的差异，实际上这部分能量预计是可以得到的”。接着，弗里施^[8]获得了裂变碎片基本上是以预计能量发射的直接证据，在用中子照射以铀填衬的电离室时，检测到有强烈的电离脉冲出现。在用钍代替电离室中的铀的情况下，得到了类似的结果，从而得出结论，某些从前被归结为来源于钍和镭的同位素的放射性，在这种情况下也是由中子轰击下发生的核裂变所致。 [英文](#)

由迈特纳和弗里施所开创的研究很快便引发了欧洲及美国物理实验室的众多研究人员的追随：哈恩和施特拉斯曼对居里与萨维奇的发现进行的证实已经向很多研究者非常明确地指出，这涉及了某些新的事物。在巴黎、伯克利、华盛顿、纽约和巴尔的摩，短短几天的时间内就得到了有关铀和钍裂变的直接证据。现在，在最初宣布之后大约三个半月的时间内，已经发表了大量的文章，这样就有必要对关于这一主题的报道进行严格的筛选。因此，在这篇综述的其余部分中将只能包括有关新现象的最值得关注的特征。 [英文](#)

也许第一个值得关注的特征就是关于钍沉淀物中的放射性元素，以前曾认为其所具有的超铀性质现在遭到了质疑。在发现裂变过程之前，对这些元素的天然X辐射研究项目在伯克利和剑桥已经展开，希望能够用通过临界吸收方法测定的辐射能量（天然的L辐射）来推断原子序数。一旦假设存在中重元素，这个问题就变得非常简单了，因为这样就可以去寻找K-辐射，而不再需要寻找较为复杂的L序列的辐射。埃布尔

森^[9]以及费瑟和布雷切尔^[10]几乎立刻从铂沉淀物的长寿命放射性中发现了碘的天然 K 辐射的证据，并且在这一观测结果的指引下，将两种最初分别被描述为类铀和类铂的产物，用化学方法确定为碲和碘。接着，在收集到的被轰击的铀的反冲产物中，几位研究者发现了其他一些所谓的超铀放射性。这些反冲产物放射性衰变速率的观测结果^[11]及化学检测的结果^[12]毫无疑问地表明，此前几乎所有的认定结果都是严重错误的。目前，对于任何可以从铀中分离出的放射性，我们都可以公正地说，认为它不是在铀核的裂变过程中产生的这一观点肯定是得不到支持的。

英文

但是，存在着一种半衰期为23分钟的重要的放射性，它是不能从铀中分离出来的，因此，不能认为它是在裂变过程中产生的。这种不可分离的放射性来源于能量约为25电子伏的中子共振俘获的过程，而有负电子参与的事实必然明确表明，一种 $Z=93$ 的核素的形成是由蜕变所导致的。可是，尽管已进行了很多细致的研究，却仍没有发现任何一种无疑是来自于该核素的转变过程的放射性。此外，关于母体核素（相应的铀的同位素半衰期 $\tau=23$ 分钟），很明显它是该物质的一种准稳态变体，在大多数情况下会发生裂变，迈特纳、弗里施和玻尔^[13]已经就这种现象对这个方面的问题进行了讨论。他们已经指出，在某些情况下发生共振俘获（ γ 射线的发射）而不是裂变，本质上并不存在任何不可理解的问题。无论如何，核分裂成两块碎片之前，必定要先通过核的巨大形变的运动形式聚集可用的能量，而如果在俘获中子之后，系统的初始状态仍然具有相当大的对称性，那么出现这种聚集的可能性就非常小了。或者如果，就像玻尔假设的那样，热中子对引起铀的裂变的影响（在轰击钍时这样的中子所产生的效果是相当弱的）是由稀有同位素铀-235的俘获所造成的，而由快中子导致的共振效应和裂变过程是由铀-238所造成的，那么甚至可以说，由于复合核天然具有形式的低稳定性导致的抵消作用，使得它在共振能量下形成时不会具有足量的激发能。就这个问题整体而言，要得到更为确定的结论显然必须等待进一步的实验研究：约里奥^[14]曾报道过中子能量发生改变时会发生不同裂变产物相对比例的变化，而这有可能被认为是对玻尔的提议的支持。但是对于分别由高能中子和热中子得到的产物，伯格、布罗斯特伦和科赫^[15]却没有从它们的衰变过程中发现任何差别。

英文

到目前为止，谈及的裂变过程仍未给出任何关于裂变碎片性质的精确陈述，这些碎片是在核分裂第一阶段产生的，而实际上至今对这一点的确切的认识也只是极少量的。对裂变产物范围进行测定可以提供一些信息。首先，它们意味着（利用铀和快中子）该过程从俘获中子时刻（向前的范围略大于向后的，这表明在复合核分裂之前，初始动量几乎没有损失^[16]）算起持续时间不足 5×10^{-13} 秒。其次，它们似乎倾向于极少量的竞争性初级过程，而不具有该过程大量出现的可能^[17]。另一方面，化学研究显示出如此丰富的放射性产物^[18]（如果没有更广泛的分布，其原子序数介于35（Br）到57（La）之间），这样就必定可以对它们的复杂性找到一些充分的解释。看来，裂变初始产物经常几乎是瞬间发射出中子^[19]，这一现象的发现，已经为这种解释提供了基础（据推测，最初以高激发态形成的核，在到达寿命较长态的过程中会发射出中子或者量子辐射）。实验也表明，甚至当这些态发生 β 衰变之后，有时产物核仍然具有足够的激发能，为了到达更稳定态，相对于辐射跃迁而言“蒸发”中子仍是一个可能的选择。关于这一点，罗伯茨、迈耶和王^[20]以及布思、邓宁和斯莱克^[21]都曾报道，在轰击铀时缓发中子的周期约为12秒和45秒，而对于钷而言，类似的特征也得到了证实。 [英文](#)

对于伴随裂变的中子蒸发过程的频率，以及这种过程中产生的中子的能量，已经有很多研究者进行过研究，但是到目前为止最为详尽的当属约里奥^[22]和他的同事，以及费米^[23]和另外一些来自纽约的研究者。看来一般性的结论是，对于铀的每一次裂变过程，至少有两个具有 10^6 电子伏数量级的平均能量的中子，最终会从残存碎片中蒸发。由于能量比这还低的中子仍然可以靠自己来产生裂变（如前所述，可能是在铀-235中），因此必须要对可能出现的放热分裂累积过程加以考虑。很明显，除了中子导致裂变的可能性之外，如果过程中消去中子的可能性充分减小，那么对任何含铀的固体物质，裂变过程最终都一定会逐渐累积。在科学文献中还没有关于该问题的直接实验的报道，但是目前我们可以指出，即使是在纯铀中，众所周知会发生非裂变俘获过程（见上），同时在固体材料中无限制产生的能量最终将会增加“热”中子的能量，直到它们引发裂变的效能大大减弱为止。已经有人利用现有数据进行过几次计算该现象过程的尝试^[24]，但是一般来说他们所依赖的前提过于理想化，因而这些数值目前还不大可能获得认可。 [英文](#)

(王耀杨 翻译；夏海鸿 审稿)

Energy of Neutrons Liberated in the Nuclear Fission of Uranium Induced by Thermal Neutrons

H. von Halban, jun. *et al.*

The fissioning of a uranium nucleus, physicists now knew, releases further neutrons, which might in principle trigger splitting in other nuclei. But researchers knew little about the energy of the released neutrons. Here Hans von Halban and colleagues in Paris clarify this matter. In a series of experiments, they used an ionization chamber to probe the distribution of energies of “fast” neutrons—that is, those having energy above 1.5 million electronvolts (1.5 MeV). The number of neutrons declines at higher energies, but some neutrons can carry away as much as 11 MeV. Knowledge of the distribution of neutron energies played an important role in the engineering of nuclear reactors, as slow neutrons trigger fission events more effectively than fast ones. [中文](#)

IT has been shown that *fast* neutrons are liberated in the process of nuclear fission induced in uranium by primary *thermal* neutrons. Two different methods of detection have been used: in the first method¹, the primary and (if any) secondary neutrons are absorbed in a medium in which an endo-energetic reaction can take place, leading to the formation of an easily detectable radioactive nucleus. If the energy threshold is situated above the maximum energy of the

primary neutrons, any positive results observed must be ascribed to the secondary neutrons. In the second method², elastic collisions of fast neutrons with heavier nuclei are observed by means of an ionization chamber filled with a gas at atmospheric pressure and connected to a linear amplifier. In order to study separately the effect due to the primary thermal neutrons, the experiment is performed with, and without, a cadmium shield between the source and the uranium mass. [中文](#)

The first method having shown us that fast secondary neutrons are produced with energies of at least 2 Mev. (sufficient to transform ^{32}S into radioactive ^{32}P in detectable quantities), we sought to ascertain, by the second method, whether neutrons of energy notably higher than 2 Mev. are also present in the secondary radiation. In our experiment, the oxygen-filled ionization chamber was placed in a nearly cubical box (9 cm. $\times$ 9 cm. $\times$ 8 cm.) containing uranium oxide and surrounded by a thick layer of paraffin wax. The source (300 mgm. $\text{Ra}\gamma + \text{Be}$), surrounded by a lead shield (5 cm. in the direction of the chamber) was buried in the wax. In order to absorb thermal neutrons, the uranium box could be screened on all sides with a cadmium foil. The pulses were recorded either in the presence or in the absence of this foil and the part of the effect (projection of oxygen nuclei by fast neutrons liberated in the uranium) due to thermal neutrons could thus be evaluated. [中文](#)

In view of the large number of of accidental pulses due to the strong γ -radiation emitted by the source, only nuclei recoiling with at least 1.5 Mev. could be taken into consideration. The distribution curve shows that the frequency of pulses observed falls off rapidly between 1.5 Mev. and 2.5 Mev.; between 2.5 Mev. and 3.7 Mev. the frequency decreases much more slowly, pulses observed in this second region being, however, very rare. The total number of pulses recorded is small (with cadmium: 84 pulses in 90 minutes; without cadmium: 161

pulses in 90 minutes); but it appears clearly that recoils with energy of about 2.5 Mev. are notably more frequent in the absence of cadmium and, therefore, that *neutrons possessing an energy of at least 11 Mev. are liberated in uranium irradiated with thermal neutrons.* 中文

The high energy of these fast neutrons shows that their parent nuclei are in a highly excited state at the moment of their liberation, which is probably simultaneous with the fission. In this way a non-negligible fraction of the fission energy is disposed of; a further fraction is carried off by the β - and γ -rays afterwards emitted by the nuclei produced in the fission. The remainder available as kinetic energy for these recoiling nuclei is therefore considerably smaller than the total amount of energy liberated in the fission process (about 200 Mev.).

中文

(143, 939; 1939)

H. von Halban, jun., F. Joliot and L.Kowarski: Laboratoire de Chimie Nucléaire, Collège de France, Paris, May 20.

References:

1. Dodé, M., von Halban, jun., H., Joliot, F., and Kowarski, L., *C.R.*, **208**, 995 (1939).
2. Szilard, L., and Zinn, W., *Phys. Rev.*, **55**, 799 (1939).

在热中子诱发的铀核裂变中释放出的中子的能量

冯·哈尔班等

物理学家现在已经知道，原则上铀核裂变释放的中子可以诱发其他核的分裂。但是研究人员关于释放中子的能量知之甚微。这里汉斯·冯·哈尔班和他巴黎的同事阐述清楚了这个问题。他们在一系列的实验中采用电离室来探测“快”中子的能量分布——即那些能量高于1.5兆电子伏的中子。中子数目随着能量升高而降低，但是一些中子携带能量多达11兆电子伏。中子能量分布的认知在核反应堆工程技术中有重要影响，因为慢中子比快中子能够更有效地诱发裂变。

英文

目前实验已表明，快中子是从初级热中子诱发的铀核裂变过程中释放出来的。已经使用了两种不同的检测方法：在第一种方法中^[1]，初级中子和次级中子（如果有的话）在一种可以发生吸能反应的介质中被吸收，以致形成了一种易于检测的放射性核。如果能量阈值高于初级中子的最大能量，那么所观测的一切肯定的结果都必定要归结为次级中子。在第二种方法中^[2]，快中子与较重核的弹性碰撞是借助电离室进行观测的，这个电离室充满着一个大气压的气体并与线性放大器相连。为了单独研究由初级热中子所产生的影响，我们在源与铀块之间，分别在加入和没有加入镉屏蔽层的两种情况下进行实验。

英文

第一种方法向我们表明，产生的次级快中子的能量至少为2兆电子伏（足以将可检测量的 ^{32}S 转变为放射性的 ^{32}P ），我们设法通过第二种方法来确定，能量明显高于2兆电子伏的中子是否也会在次级辐射中出现。在我们的实验里，将充满氧气的电离室置于装有氧化铀且四周用厚的固体石蜡层包裹的近似立方（9厘米×9厘米×8厘米）的盒子中，将

用铅屏蔽层包裹（在电离室的方向上的厚度为5厘米）的源（300毫克镭铍源）埋入石蜡之中。为了吸收热中子，我们可以用镉箔将铀盒的所有面都遮挡起来。在镉箔存在或者不存在的两种情况下记录脉冲，并且由此可以估算出受到热中子影响的部分（铀核所释放的快中子导致氧核的反冲）。 [英文](#)

鉴于由源发出强 γ 辐射所导致随机脉冲的数目很大，我们只考虑反冲能量至少为1.5兆电子伏的核。分布曲线显示，观测到的脉冲频率在能量1.5兆电子伏到2.5兆电子伏之间快速下降；在能量2.5兆电子伏到3.7兆电子伏之间，频率的下降减慢了很多，不过，在这第二个能量区域所观测到的脉冲非常稀少。记录到的总的脉冲数很少（使用镉时：90分钟里有84个脉冲；不使用镉时：90分钟里有161个脉冲）；但是似乎很明确的是，在没有镉时能量约为2.5兆电子伏的反冲明显出现得更为频繁，因此，用热中子辐照铀时释放出至少具有11兆电子伏能量的中子。

[英文](#)

这些快中子所具有的高能量表明，在它们释出时其母核处于高激发态，释出与裂变可能是同时发生的。这样，裂变能中不容忽视的一部分就被转移走了；更大的一部分则被在裂变中生成的核通过发射 β 射线和 γ 射线带走了。因此，能够作为反冲核的动能的剩余能量就明显少于裂变过程中释放出的能量总量（约为200兆电子伏）。 [英文](#)

（王耀杨 翻译；夏海鸿 审稿）

Nuclear Reactions in the Continuous Energy Region

N. Bohr *et al.*

The chief interest of this Letter to *Nature* is its authors: Niels Bohr at Copenhagen was the acknowledged father of quantum mechanics, Rudolf Peierls was a graduate research worker at Copenhagen who eventually migrated to Britain and was the designer of the thermal diffusion process for separating isotopes, and George Placzek was a close colleague of the other two. The point of their letter was to emphasise the utility of an idea due to Bohr that when nuclei collide with each other they first form a “compound nucleus” which can then split up in several different ways. [中文](#)

IT is typical for nuclear reactions initiated by collisions or radiation that they may, to a large extent, be considered as taking place in two steps: the formation of a highly excited compound system and its subsequent disintegration or radiative transition to a less excited state. We denote by $A, B, \dots$ the possible alternative products of the reaction, specified by the nature, internal quantum state, and spin direction both of the emitted particle or photon and of the residual nucleus and the orbital momentum. Further, we call $P_A, P_B \dots$ the probabilities, per unit time, of transitions to $A, B, \dots$ respectively, from the compound state. [中文](#)

The cross-section of the reaction $A \rightarrow B$ is then evidently

$$\sigma_B^A = \sigma^A \frac{P_B}{P_A + P_B + \dots}, \quad (1)$$

where σ^A is the cross-section for a collision in which, starting from the state A , a compound nucleus is produced. This formula implies, of course, that we are dealing with energies for which the compound nucleus can actually exist, that is, that we are either in a region of continuous energy values or, if the levels are discrete, that we are at optimum resonance. Moreover, it is assumed that all possible reactions, including scattering, proceed by way of the compound state, neglecting, in particular, the influence of the so-called “potential scattering”, where the particle is deflected without actually getting into close interaction with the individual constituents of the original nucleus. [中文](#)

On these assumptions a very general conservation theorem of wave mechanics¹ yields the relation

$$\sigma^A = \frac{\lambda^2}{\pi} (2l + 1) \frac{P_A}{P_A + P_B + \dots}, \quad (2)$$

where λ is the wave-length of the incident particle and l is the angular momentum. [中文](#)

In the case of discrete levels, (1) and (2) give the same cross-section as the usual dispersion formula, if one applies it to the centre of a resonance level and neglects the influence of all other levels. In this case we have for each resonance level a well-defined quantum state of the compound nucleus, and its properties, in particular the probabilities $P_A, P_B, \dots$ then cannot depend on the kind of collision by which it has been formed, that is, they would be the same if we had started from the fragments B , or C , ... instead of A . [中文](#)

In the case of the continuum, however, where there are many quantum states with energies that are indistinguishable within the life-time of the compound nucleus, the actual state of the system is a

superposition of several quantum states and its properties depend on their phase relations, and hence on the process by which the compound nucleus has been produced. [中文](#)

This dependence is made particularly obvious if we consider the formula

$$\overline{\sigma^A} = \frac{\hbar}{2} \rho \lambda^2 (2l + 1) P_A^0, \quad (3)$$

for the mean value of the cross-section over an interval containing many levels, which follows from the well-known considerations of detailed balancing. Here ρ is the density per unit energy of levels (of suitable angular momentum and symmetry) of the compound nucleus. P_A^0 is the probability for process A in statistical equilibrium and thus refers to a micro-canonical ensemble of compound states built up from the fragments $A, B \dots$ respectively, with proper statistical weights.

[中文](#)

In the case of discrete levels, where formula (3) can also be derived directly from the dispersion formula, P_A^0 is simply an average over the individual levels of the probability P_A , which in this case is well defined. [中文](#)

In the continuum, (3) must be identical with (2), since the cross-section does not vary appreciably over an energy interval containing many levels, and hence, comparing (2) and (3)

$$\frac{P_A^{(A)}}{P_A^0} = \frac{\pi}{2} \hbar \rho (P_A^{(A)} + P_B^{(A)} + \dots) = \frac{\pi}{2} \frac{\Gamma^{(A)}}{d}, \quad (4)$$

where the superscript A has been added to the probabilities occurring in (1) in order to show explicitly the dependence on the mode of formation, and where $\Gamma^{(A)}$ is the total energy width of the compound state concerned and $d = \frac{1}{\rho}$ the average level distance. In the

continuum, where $\Gamma(A) \gg d$, the probability $P_A^{(A)}$ of re-emitting the incident particle without change of state of the nucleus will thus be much larger than the probability of the same process in a compound nucleus produced in other ways. 中文

While the arguments used so far are of a very general character, more detailed considerations of the mechanism of nuclear excitation are required for a discussion of the dependence $P_B^{(A)}$ of the mode A of the compound nucleus provided $A = B$. 中文

One can think of cases in which such a dependence must obviously be expected; in fact, if a large system be hit by a fast particle, the energy of excitation might be localized in the neighbourhood of the point of impact, and the escape of fast particles from this neighbourhood may be more probable than in statistical equilibrium. Further, if the system had modes of vibration very loosely coupled, the excitation of one of them, for example by radiation, would be unlikely to lead to the excitation of a state of vibration made up of very different normal modes, even though the state may be quite strongly represented in statistical equilibrium. 中文

In actual nuclei, however, the motion cannot be described in terms of loosely coupled vibrations, nor would one expect localization of the excitation energy to be of importance in nuclear reactions of moderate energy. If we suppose that there are no other special circumstances which would lead to a dependence of $P_B^{(A)}$ on A , it is thus a reasonable idealization to assume that, even in the continuum, all $P_A^{(A)}$ are equal to P_B^0 , except, of course, for $A = B$, where we have seen in (4) that the phases are necessarily such as to favour the re-emission of the incident particle. 中文

A typical case of a reaction in the continuum is the nuclear photo-effect in heavy elements, produced by γ -rays of about 17 mv. In the first experiments of Bothe and Gentner, there seemed to be marked

differences between the cross-sections of different elements, but the continuation of their investigations² indicated that these differences can be accounted for by the different radioactive properties of the residual nuclei, and that the cross-sections of all heavy nuclei for photo-effect are of the order of $5 \times 10^{-26} \text{ cm}^2$. [中文](#)

In previous discussions, based on formulae (1) and (2), where the distinction between $P_A^{(4)}$ and P_A^0 was not clearly recognized, it was found difficult, however, to account for photo-effect cross-sections of this magnitude. In fact, if one estimates the probability of neutron escape P_B at about $10^{17} \text{ sec.}^{-1}$, one should have for P_A $10^{15} \text{ sec.}^{-1}$ and as long as this was taken as P_A^0 it seemed much too large, since it evidently must be much smaller than the total radiation probability, estimated at about 10^{15} , which included transitions to many more final levels besides the ground state. [中文](#)

We see now, however, that $P_A^{(4)}$ is here considerably larger than P_A^0 , since the level distance at the high excitations concerned is probably of the order of 1 volt, whereas the level width corresponding to the above value of P_B is about 100 volts. From (4), or more directly from (3), P_A^0 is thus seen to be only about $10^{13} \text{ sec.}^{-1}$, which would appear quite reasonable. [中文](#)

(144, 200-201; 1939)

N. Bohr, R. Peierls and G. Placzek: Institute of Theoretical Physics, Copenhagen, July 4.

References:

1. The details of this and of the other arguments of this note will be published in the *Proceedings of the Copenhagen Academy*.
2. Bothe, W., and Gentner, W., *Z. Phys.*, **106**, 236 (1937); **112**, 45 (1939).

连续能量区域的核反应

玻尔等

这篇寄给《自然》的通讯最令人感兴趣的是他的作者：哥本哈根的尼尔斯·玻尔，他是众所周知的量子力学之父，鲁道夫·佩尔斯为哥本哈根的研究生，最后移居英国，是应用热扩散过程来分离同位素方法的设计者，乔治·普拉切克是上述两位作者的亲密同事。他们的这篇文章的要点是强调玻尔的关于核碰撞的观点，他们认为，原子核在发生碰撞时首先形成“复合核”，这种复合核可以通过多种方式分裂。 [英文](#)

通常认为，由碰撞或者辐射引发的核反应在很大程度上分为两步发生：首先形成一个处于较高激发态的复合体系，然后通过衰变或辐射跃迁到较低的激发态。我们用 $A, B, \dots$ 表示反应中可能出现的两类不同的产物，并通过发射出的粒子或光子及残余核的性质、内在量子态、自旋方向及轨道角动量来决定。此外，我们定义 $P_A, P_B, \dots$ 为单位时间内由复合态分别跃迁到 $A, B, \dots$ 态上的概率。 [英文](#)

显然， $A \rightarrow B$ 反应的有效截面为：

$$\sigma_B^A = \sigma^A \frac{P_B}{P_A + P_B + \dots} \quad (1)$$

式中 σ^A 为从 A 状态发生碰撞产生一个复合核的有效截面。这个公式表示，我们讨论的能量是这个复合核能够真正存在的能量，也就是说，我们或者有一个能量连续的区域，或者如果能级是分立的，我们将得到最适合的共振态。而且，假定所有可能发生的反应，包括散射，都是通过复合状态进行的，特别忽略了被称作“势散射”的影响，在“势散射”中，粒子的轨迹发生偏斜，因而未能与原始原子核中的某个粒子发生近距离

的相互作用。 英文

基于这些假定，根据波动力学^[1]普适的守恒定理给出以下关系式：

$$\sigma^A = \frac{\lambda^2}{\pi} (2l + 1) \frac{P_A}{P_A + P_B + \dots} \quad (2)$$

式中 λ 为入射粒子的波长， l 为其角动量。 英文

假如人们应用色散公式于一个共振能级的中心而且忽略了所有其他能级的影响的话，对于分立的能级，由式（1）和式（2）给出的有效截面与通常色散公式得到的结果相同。在这种情况下，我们将为复合核中的每一个共振能级确定一个明确的量子态，同时它的特性，尤其是概率 $P_A, P_B, \dots$ 并不依赖于通过什么类型的碰撞而形成，也就是说反应从阶段 B 或者 C 及其他碎片开始与从 A 开始得到的结果是一样的。 英文

然而，对于能量连续的情况来说，在复合核的寿命期内存在着很多不易区分能量的量子态，系统的实际状态就是多个量子态的叠加，系统的性质取决于它们的相位关系，因此取决于复合核的形成过程。 英文

如果我们考虑以下的公式，这种相关性就会变得非常明显：

$$\overline{\sigma^A} = \frac{\hbar}{2} \rho \lambda^2 (2l + 1) P_A^0 \quad (3)$$

对于在一个包含若干能级的区间中截面的平均值，它服从著名的细致平衡原理。式中 ρ 在这里表示复合核中能级（具有适当的角动量 and 对称性）的每单位能量上的密度， P_A^0 为 A 过程的统计平衡概率，因此引出一个由各自具有特有的统计权重的碎片 $A, B, \dots$ 构成的复合状态的微正则系综。 英文

对于分立能级的情况，式（3）也可以直接由色散公式导出，在这种情况下我们可很容易的定义 P_A^0 为对概率 P_A 的单个能级上的简单的平均值。 英文

对于能量连续的情况，式（3）和式（2）必须一致，因为有效截面

在一个包含多个能级的能量区间中的变化并不明显。因此，比较式（2）和式（3），我们会得出：

$$\frac{P_A^{(A)}}{P_A^0} = \frac{\pi}{2} \hbar \rho (P_A^{(A)} + P_B^{(A)} + \dots) = \frac{\pi}{2} \frac{\Gamma^{(A)}}{d} \quad (4)$$

其中，在式（1）中的概率上添加上标A是为了明确地表示其与形成模式的相关性， $\Gamma^{(A)}$ 是对应复合态的总能级宽度， $d = \frac{1}{\rho}$ 表示能级的平均间距。在能量连续的体系中，当 $\Gamma^{(A)} \gg d$ 时，在不改变原子核状态的条件下

再次发射入射粒子的概率 $P_A^{(A)}$ 会比在以其他方式形成的复合核中发生同样过程的概率大得多。 [英文](#)

前面的论述针对的都是总体上的特征，要进一步考量核激发机制需要讨论当 $A=B$ 时， $P_B^{(A)}$ 对复合核中模式A的依赖性。 [英文](#)

人们可以设想一些这种依赖性肯定存在的情况，实际上，如果一个很大的系统被一个快速粒子撞击，激发的能量也许只局限于碰撞点附近，快速粒子逃离该区域的可能性比到达统计平衡时的概率大。而且，如果这个系统具有松散耦合的振动模式，它们当中一个被激发，比如通过辐射，很难导致一个差异很大的普通模式组成的振动态被激发，即使这种状态在统计平衡中占有很大的优势。 [英文](#)

然而，在实际的原子核中，我们不能用松散耦合的振动模式来描述运动，也不能期望激发能的局域化对中等能量的核反应的重要性。如果我们假定没有其他的特殊情况可以导致 $P_B^{(A)}$ 对A的依赖性，那么除去 $A=B$ 的情况以外，理想化地假定所有 $P_A^{(A)}$ 都等于 P_B^0 是合理的，即使是在能量连续的体系中，正如我们在式（4）看到的那样，该状态必然更有利于产生入射粒子的再发射过程。 [英文](#)

在能量连续体系中的一个典型反应是重元素原子的光电效应，由17毫伏的 γ 射线引发。博特和根特纳在最初的实验中发现，不同元素的有效截面明显不同，但是他们后来的研究^[2]又表明这种不同可以用残余核子的放射性差异来解释，而且所有重元素在光电效应中的有效截面均为 5×10^{-26} 平方厘米的量级。 [英文](#)

在前面基于式（1）和（2）的讨论中，由于没有清楚地认识到 $P_A^{(A)}$ 和 P_A^0 之间的差别，我们发现要解析这种大小的光电效应的有效截面是有困难的。事实上，如果人们估算中子逃逸的概率 P_B 约为每秒 10^{17} ，那么 P_A 应为每秒 10^{15} ，但如果认为 P_A^0 也具有同样的数值，那就太大了，因为它显然必须远远小于整个辐射的概率，整个辐射的概率约为 10^{15} ，其中包括向基态以及更多其他最终能级的跃迁过程。 [英文](#)

然而，我们现在得出，在本文 $P_{(A)}$ 要远大于 P_A^0 ，因为在高激发态中能级间距的数量级大约为1电子伏，但是对于上面的 P_B 值得到的能级宽度大约为100电子伏。从式（4），或者更直接地从式（3）中看出， P_A^0 的合理值只有每秒 10^{13} 左右。 [英文](#)

（胡雪兰 翻译；王乃彦 审稿）

The Scattering by Uranium Nuclei of Fast Neutrons and the Possible Neutron Emission Resulting from Fission

L. Goldstein *et al.*

Here Goldstein, Rogazinski and Walen describe experiments measuring how neutrons interact with uranium nuclei. They used neutrons from a polonium-beryllium source to irradiate samples of lead oxide and uranium oxide, and detected neutrons with an ionization chamber. They are able to estimate the “cross-section”—the “size” of the nuclei as seen by the neutrons—for neutrons that are scattered with or without a change in energy. As they noted, their cross-section was somewhat higher than previous estimates, implying that neutrons can travel a little less far than thought in uranium. This suggested, in turn, that a critical mass for a chain reaction might also be smaller than previously suspected. [中文](#)

THE work to be described concerns only fast neutrons, and its object is the study of their scattering by uranium and the possible neutron emission which accompanies the fission of the nucleus. [中文](#)

The experiments were performed with a polonium plus beryllium source equivalent to 3 mC. of radon plus beryllium. An ionization

chamber surrounded with 2.5 cm. lead, filled with hydrogen at a pressure of 35 atm., was used as a neutron detector. The insulated electrode was connected to a compensated electrometer valve¹, the grid leak being 10^{11} ohms and the sensitivity 1.2×10^{-15} amp./div. on the scale. 中文

We have employed two experimental arrangements in which the source was placed (1) between the chamber and the substance used as scatterer, the nature and the thickness of which were variable; (2) in the centre of a cube of 16 cm. side, alternately filled with uranium oxide (specific gravity, $d=4.0$) and lead oxide (compressed to $d=3.8$).

中文

The first type of experiment gave us the total scattering cross-section, which is, as can be shown, $\sigma_t=\sigma_e+k_i\sigma_i$; for uranium oxide $\sigma_t=\sigma_e+k_i\sigma_i+k_r\nu_r\sigma_r$, where σ_e , σ_i , σ_r are respectively the average cross-sections of elastic and inelastic scattering and of fission; ν_r is the average number of neutrons produced per fission; k_i and k_r are the average efficiency factors of the chamber for the neutrons having undergone an inelastic collision or for the neutrons resulting from fission. The efficiency for the direct neutrons was taken to be unity, $k=1$. For neutrons elastically scattered by nuclei of sufficiently high mass, $k_e=k=1$. We have calculated k , taking into account the size of the chamber, the cross-section for proton projection, etc. The spectrum of polonium plus beryllium neutrons has been considered² to contain 50 percent of neutrons of W_n less than 10^5 ev. We thus obtain:

$10^{-6}W_n$	0.1	0.5	3	5	10	ev.
k	0.3	1	1.9	1.7	1.2	

中文

In view of a possible extrapolation that would give $\sigma_e+k_i\sigma_i$ for uranium, we have in the same way experimented with scattering by lead oxide, lead, copper and zinc. 中文

The results of the first experiment were as follows:

Substance	Cu	Zn	Pb	PbO ₂	UO ₂	(O) _{calc.}	(U) _{calc.}
$\sigma_t \times 10^{-24} \text{ cm}^2 (\pm 10\%)$	2.2	2.3	5.4	9.5	14.4	2	10.3

中文

The values for uranium and oxygen are calculated on the assumption of the additivity of the cross-sections in lead oxide and uranium oxide.

中文

The second experiment gives us, in the first approximation, the absorption coefficient $(1-k_i)\sigma_i + (1-k_r\nu_r)\sigma_r$, the value of σ_e being only as a correction term in the determination of the mean free path λ and the average distance L travelled by the neutrons before they escape from the whole mass, which is supposed spherical, the radius being r and $L = r \left(1 + \frac{1}{2} \frac{r}{\lambda}\right)$. This experiment, taking into account the results of the previous experiments, gives for lead, $(1 - k_i)\sigma_i \simeq 2 \times 10^{-24} \text{ cm}^2$. Assuming that σ_i can reach 30 percent of σ_e ³, this gives $k_i(\simeq)0$

中文

With the exception of uranium, for which one must consider not only σ_i , but also $\nu_r\sigma_r$, it is probable that σ_t is not very different from σ_e because of the small value of k_i .

中文

In the case of uranium, however, we have,

$$(1 - k_i)\sigma_i + (1 - k_r\nu_r)\sigma_r \simeq 0.9 \times 10^{-24} \text{ cm}^2 \tag{1},$$

or, by adding to σ_t , thus eliminating k_i and k_r ,

$$\sigma_e + \sigma_i + \sigma_r \simeq 11.2 \times 10^{-24} \text{ cm}^2. \tag{2}.$$

中文

If it is supposed that each fission produces radioelements, the cross-section measured by Joliot, and by Anderson *et al.*⁴ would be identical

with σ_r , which they found to be $\sigma_r \approx 10^{-25} \text{cm}^2$. In this case we see that $(\sigma_e + \sigma_i)$ is much greater ($\approx 11.1 \times 10^{-24} \text{cm}^2$) than that given by an extrapolation ($\approx 6 \times 10^{-24} \text{cm}^2$) [中文](#)

On the other hand, it results from (1) that, if the value of σ_i is comparable to that of the next elements ($1 \text{ to } 2 \times 10^{-24} \text{cm}^2$), ν_r can, with plausible assumptions as to the coefficients k_i and k_r , take variable values, for example, from 1 to 5, or even more. [中文](#)

One can see that, so long as σ_i is not determined separately, the experiments of the type described do not allow us to determine ν_r and σ_r (characteristics of the fission), or to conclude that neutrons are liberated; or *a fortiori*, to form a conclusion as to the possibility of chain reactions, contrary to the results of similar experiments⁵. [中文](#)

The only suitable case for showing with certainty, by means of an ionization chamber, the production of neutrons, would be that in which, by the use of a sufficient quantity of uranium, the chain mechanism would give multiplication of neutrons, if such chain is realizable⁶. [中文](#)

In conclusion, it results from these experiments with neutrons of polonium plus beryllium that the sum of the cross-sections $\sigma_e + \sigma_i + \sigma_r$ for the uranium nucleus is $(11.2 \pm 1.5)10^{-24} \text{cm}^2$. This value implies a mean path in uranium much shorter than that usually admitted; this suggests that smaller masses than those hitherto expected might be used to show chain fission. [中文](#)

(144, 201-202; 1939)

La. Goldstein, A. Rogozinski and R. J. Walen: Laboratoire Curie, Institut du Radium, Paris, 5, July 13.

References:

1. Rogozinski, A., *C.R.*, **208**, 427 (1939).

2. Auger, P., *J. Phys. Radium*, **4**, 719 (1933).
3. Seaborg, G. F., Gibson, G. E., and Graham, D. C., *Phys. Rev.*, **52**, 408 (1937).
4. Joliot, F., *J. Phys. Radium*, **10**, 159 (1939). Anderson, H. L., Booth, E. T., Dunning, J. R., Fermi, E., Glasoe, G. N., and Slack, F. G., *Phys. Rev.*, **55**, 511 (1939).
5. Haenny, C., and Rosenberg, A., *C.R.*, **208**, 898 (1939).
6. v. Halban, H., Joliot, F., and Kowarski, L., *Nature*, **143**, 680 (1939). Perrin, F., *C.R.*, **208**, 1394, 1573 (1939).

铀核的快中子散射与可能源于裂变的中子发射

戈尔德施泰因等

本文戈尔德施泰因、罗格兹尼斯基和瓦伦描述了测量中子与铀核如何相互作用的实验。他们使用钋-铍源的中子辐照氧化铅和氧化铀的样品，并用电离室探测中子。他们可以估算出有能量变化和无能量变化两种实验情况下散射中子的“截面”，即中子与核碰撞的“尺寸”。正如他们所说的，他们计算得出的截面比先前估算的稍高，这意味着中子在铀中的行程比想象的稍小。反过来说，这也表明了链式反应的临界质量值也可能小于原先估算的值。 [英文](#)

本文所描述的内容仅涉及快中子，目标是研究铀的快中子散射以及核裂变过程中可能伴随的中子发射。 [英文](#)

实验是用一个钋-铍源（相当于3毫居氡-铍源）完成的。我们用2.5厘米厚的铅板包围电离室来作为中子探测器，室内充满了35个大气压的氢气。绝缘电极与补偿静电计电子管相连接^[1]，栅漏电阻为 10^{11} 欧姆，标度灵敏度为每分度 1.2×10^{-15} 安培。 [英文](#)

我们使用了两套实验装置：（1）实验源位于电离室和作为散射体的物质之间，其中散射体物质的性质和厚度是可变的；（2）实验源位于边长为16厘米的立方体中心，其中交替填充氧化铀（比重 $d = 4.0$ ）和氧化铅（压缩后比重 $d = 3.8$ ）。 [英文](#)

第一种实验给出了总的散射截面，可以表示为 $\sigma_t = \sigma_e + k_i \sigma_i$ ；对于氧化铀，散射截面为 $\sigma_t = \sigma_e + k_i \sigma_i + k_r \nu_r \sigma_r$ ，其中， σ_e 、 σ_i 、 σ_r 分别是弹性散射、非弹性散射及裂变的平均截面； ν_r 是每次裂变产生的平均中子数； k_i

和 k_r 分别是电离室对发生非弹性碰撞的中子和裂变产生的中子的平均效率因子；直接入射中子的效率因子取为1，即 $k = 1$ 。对于由质量足够高的原子核弹性散射的中子， $k_e = k = 1$ 。我们在考虑了电离室的尺寸、质子投射截面等值后计算了 k 的值。现在认为[2]，钋-铍源的中子能谱包含了 W_n 小于 10^5 电子伏的中子的50%。因此，我们得到：

$10^{-6}W_n$	0.1	0.5	3	5	10	电子伏
k	0.3	1	1.9	1.7	1.2	

英文

鉴于一种可行的外推法可以给出铀的 $\sigma_e + k_i\sigma_i$ 值，我们以相同的方法用氧化铅、铅、铜和锌与中子发生散射进行实验。

英文

第一种实验结果如下：

物质	Cu	Zn	Pb	PbO ₂	UO ₂	(O)计算值	(U)计算值
$\sigma_i \times 10^{-24}$ 平方厘米 ($\pm 10\%$)	2.2	2.3	5.4	9.5	14.4	2	10.3

英文

假定氧化铅和氧化铀截面具有可加性的前提下，我们计算了铀和氧的截面值。

英文

第二种实验我们在一阶近似下给出了吸收系数 $(1 - k_i) \sigma_i + (1 - k_r \nu_r) \sigma_r$ 的值， σ_e 的值只是作为中子从假设为球形的块状物体逃逸前的测定平均自由程 λ 和中子穿行平均距离 L 的修正项，球块的半径是 r ，且 $L = r (1 + \frac{1}{2} \frac{r}{\lambda})$ 。考虑到以前实验的结果，这个实验给出了铅的 $(1 - k_i) \sigma_i \simeq 2 \times 10^{-24}$ 平方厘米。假定 σ_i 的值能达到 σ_e 值[3]的30%，则有 $k_i (\simeq) 0$ 。

英文

对于铀我们不仅要考虑 σ_i ，还要考虑 $\nu_r \sigma_r$ ，而对于其他物质很有可能由于 k_i 的值很小， σ_t 与 σ_e 的值相差并不大。

英文

对于铀的情况，我们有

$$(1 - k_i) \sigma_i + (1 - k_r \nu_r) \sigma_r \simeq 0.9 \times 10^{-24} \text{ 平方厘米}$$

(1)

或者，在式子两边加上 σ_t 将消掉 k_i 和 k_r ，得到

$$\sigma_e + \sigma_i + \sigma_r \simeq 11.2 \times 10^{-24} \text{ 平方厘米} \quad (2)$$

英文

如果假定每次裂变都产生放射性元素，约里奥和安德森等人^[4]测得的截面值则与 σ_r 一致，他们测得的结果是 $\sigma_r \approx 10 \cdot 10^{-25}$ 平方厘米。在这种情况下，我们看到， $(\sigma_e + \sigma_i)$ 的值（ $\approx 11.1 \times 10^{-24}$ 平方厘米）远大于外推法所给出的值（ $\approx 6 \times 10^{-24}$ 平方厘米）。 英文

另一方面，根据（1）式的结果可知，如果 σ_i 的值与接下来 σ_r 的值（ $1 \times 10^{-24} \sim 2 \times 10^{-24}$ 平方厘米）相近的话，在 k_i 和 k_r 系数运用合理的假定下， ν_r 的值是可变的，例如可以从1取到5甚至更大的值。 英文

可以看到，只要不能独立地测定 σ_i 值，在这类实验中我们就不能测定 ν_r 和 σ_r （分裂的特征）的值，也就不能断定是否释放了中子；更不用说得到可能发生链式反应的结论了，这与类似实验的结果^[5]相反。

英文

通过使用电离室，唯一可以确定的合理情况是，对于中子的产生，如果链式反应可以实现的话^[6]，通过使用足量的铀，链式反应就可以产生出中子的倍增效应。 英文

综上所述，通过运用钋-铍中子源的这些实验可知，对铀核截面求和，即 $\sigma_e + \sigma_i + \sigma_r = (11.2 \pm 1.5) \times 10^{-24}$ 平方厘米。这个值表明铀中的平均自由程远小于通常公认的值；而这也意味着可以用比现在预期的更小的质量来实现链式核裂变。 英文

（沈乃澍 翻译；张焕乔 审稿）

Recent Experimental Results in Nuclear Isomerism

B. Pontecorvo

The idea that two atomic nuclei might be identical in their physical composition and mass but nevertheless might differ in their radioactive properties goes back to 1917 and to Frederick Soddy, one of the pioneers of radioactive studies. It is equivalent to saying that isomeric nuclei are capable of decaying by more than one route. With the discovery of artificial radioactivity, pairs of isomeric nuclei became more common. Bruno Pontecorvo, who migrated from France to Britain in 1940, had made a special study of isomeric nuclei and published this account of their properties a few months before the Second World War began. [中文](#)

THE hypothesis that two atomic nuclei indistinguishable in respect of atomic and mass number could nevertheless have different radioactive properties (the hypothesis of nuclear isomerism) was put forward for the first time by Soddy¹ in 1917. In 1921 uranium Z was discovered by Hahn²; by studying the chemical and radioactive properties of this element, Hahn deduced that uranium Z and uranium X₂ are isomeric nuclei. The problem of uranium Z has been taken up recently by Feather and Bretscher (*Proc. Roy. Soc.*, **165**, 542; 1938). It should be noted that, for many years, uranium Z and uranium X₂ were the only known example of an isomeric pair. [中文](#)

After the discovery of artificial radioactivity, the study of isomerism received considerable impetus on account of the experimental material assembled in the course of research on artificial radio-elements. The first *certain* example of an isomeric pair to which it has been possible to attribute a mass number ($A = 80$) in the domain of the artificial radio-elements was furnished³ by the study of the radioactivity produced in bromine by neutrons (slow and fast) and by γ -rays of great energy. [中文](#)

Then, as the experimental material on artificial radio-elements has increased, the number of pairs of nuclei which are undoubtedly isomeric has grown to such an extent that it is not possible to quote here all the investigations which have been published on the question. More than thirty such pairs are known and there is no doubt that the number still unknown is much greater. We can say, now, *that nuclear isomerism is by no means an exceptional phenomenon*. [中文](#)

It is natural to think that the physical difference between two isomeric nuclei is connected with two states of different excitation of the same nucleus (let us say ground state and first excited state). But in this case, how could the upper state be metastable, that is, how could it live for any length of time (greater than one day, in some cases)? By what mechanism would it be preserved from destruction in a very short time by the emission of an electromagnetic radiation? Weiszäcker has answered this question⁴. [中文](#)

According to Weiszäcker's *hypothesis*, nuclear isomerism may be explained by assuming that *the lowest excited state of the nucleus has an angular momentum differing by several units from that of the ground state*. Selection rules may then be invoked to weaken considerably the probability per unit of time of the transition from the upper to the ground state of the nucleus. Of course, experiments which make it possible to test the truth of Weiszäcker's hypothesis are of great interest. [中文](#)

One of the most important points is the study of the γ -radiation eventually emitted in the transition from one isomeric state to another: I say “eventually emitted” because, the nucleus being radioactive, the upper state corresponding to one of the isomeric forms may be destroyed by an ordinary β transition. The γ -ray- β -ray branching ratio will depend on the relative life-times for the two modes of decay. The first researches made to observe this γ -radiation failed. But it should be noted⁵ that the considerable difficulty in detecting this radiation might be due to the fact that transitions between isomeric nuclei can be strongly converted: in this case electrons of small energy would be emitted and not γ -rays. 中文

The very complete theory of the internal conversion of radiations emitted in the transitions between isomeric states⁶, given by Hebb and Uhlenbeck, Dancoff and Morrison, has shown that these radiations must have internal conversion coefficients of approximately 1. Since these calculations are based on Weiszäcker’s hypothesis, it can be concluded that *experiments which prove that the conversion coefficient in question is very high would indicate, to a certain extent, that Weiszäcker’s hypothesis is correct.* 中文

Indeed, in the case of the isomerism of radio-rhodium, Pontecorvo⁷ has observed a radiation of low-energy electrons, which he interpreted as an electron line emitted in the transition from the metastable state to the ground state of the nucleus.* 中文

At the present time, after a number of recent experiments, *there is no longer any doubt as to the fact that these transitions are generally strongly converted.* In particular, in the cases of isomeric nuclei of radio-bromine⁸ and of element 43⁹, strong lines of conversion electrons have been photographed in the Wilson chamber or in the magnetic spectrograph. Of course, the internal conversion is accompanied by emission of X-rays: as a rule, the analysis of these rays is an invaluable test in the interpretation of these phenomena^{9,10}. 中文

It is interesting to find possible genetic relations between isomeric states of the same nucleus (β -radioactive): in this direction an extremely brilliant method has been described by Segré, Halford and Seaborg¹¹, who have succeeded in *separating*, one from the other, the two isomeric forms of radio-bromine. The principle of their method is as follows. Suppose the element, of which the isomeric states are being studied, can give compounds suitable for the application of the Szilard-Chalmers method of concentration. When the isomer in the upper state decays to the lower state, there is a γ -ray emission: corresponding recoil may be sufficient to knock the decayed atom out of the compound. The daughter activity can then be separated, as in the Szilard-Chalmers method. [中文](#)

This method, which has been successfully applied in several cases¹², can then be used (a) to separate known isomers in some cases; (b) to discover the existence of isomeric pairs, still unknown, in the study of artificial radioactivity. [中文](#)

Moreover, it has given a striking new proof that the transitions between isomeric states are strongly converted: in effect, the recoil due to the γ -emission is not sufficient to knock the decayed atom out of the compound, while the recoil of a conversion electron *can* be sufficient. [中文](#)

So far we have discussed radioactive isomers: the isomerism in this case, implies a difference in the life-times of the isomers. It has been noticed by Pontecorvo⁵ that β -stable nuclei with a metastable excited state ought not to be very rare and should be revealed by the study of the radiation emitted by this metastable state. These nuclei are interesting for the understanding of nuclear isomerism, because the radiation corresponding to the transition from one isomeric state to the other is not troubled by the presence of β - or γ -rays. It should be possible to obtain a β -stable nucleus in a metastable state, after a nuclear transmutation or a radioactive disintegration. [中文](#)

Dodé and Pontecorvo¹³, by bombardment of cadmium with fast neutrons, have obtained an activity ($T=50$ min.) which chemical proofs have shown to be due to an isotope of cadmium. On the other hand, there is no question of a reaction of simple neutron capture or of an $n,2n$ reaction. They interpreted the soft radiation emitted by cadmium (50 min.) as proceeding from a metastable state of an isotope of cadmium; the reaction of excitation without capture by fast neutrons (reaction n,n), having a considerable cross-section (some 10^{-24} cm.²), it is not impossible, indeed, that part of the nuclei so excited might fall into a metastable state. [中文](#)

Segré and Seaborg⁹ have observed a metastable state of element 43, decaying (only a line spectrum of electrons) with a 6-hour period into the ground state, which is stable or perhaps radioactive with a long life: the 6-hour activity is daughter of a β -radioactive molybdenum.

[中文](#)

A very interesting case has been observed and studied thoroughly by Goldhaber, Szilard and Hill¹⁴. They have obtained by the n,n reaction already quoted, a metastable state ($^{115}\text{In}^*$) of ^{115}In , decaying with a period of 4.1 hours; moreover, the same state can be obtained after the disintegration of a radio-cadmium ($T=2.5$ days). The radiation emitted by $^{115}\text{In}^*$ has not yet been sufficiently studied; its properties are of the greatest interest both for the understanding of the nuclear isomerism and for that of isobaric pairs. In effect, ^{115}In and ^{115}Sn are one of the rare cases of stable neighbouring isobaric nuclei: $^{115}\text{In}^*$ might then decay into ^{115}Sn (β -emission) or into ^{115}In , or into both together. [中文](#)

The same metastable state of ^{115}In has been obtained also by irradiating indium with 5.8 Mev. protons (reaction p,p), by Barnes and Aradine¹⁵. Nevertheless, it is not yet clear whether the mechanism of nuclear excitation is that discussed by Weisskopf, that is, excitation by the action of the electric field of the proton¹⁶. [中文](#)

In all these cases and in others studied more recently¹⁷, the metastable states of stable isotopes are obtained from *nuclear transmutations*.

[中文](#)

Lazard and Pontecorvo¹⁸ have tried a new method, by which *it would be impossible to transmute the nucleus* and, consequently, to obtain artificial radio-elements, the presence of which may interfere with the investigation. [中文](#)

This method consists of irradiating the target with a continuous spectrum of X-rays, the energy of which is less than the dissociation energy of the nuclei. Suppose the radiated nuclei have a metastable state; the X-rays may excite higher levels of the nuclei; a part of the nuclei thus excited can fall into the metastable state, and it is the radiation from this state which can be observed. The maximum energy of the continuous spectrum utilized was 1,850 kilovolts: indium gives an activity of approximately 4 hours period, which is obviously due to the same metastable state $^{115}\text{In}^*$, of which we have already spoken. Similar results on the stable nuclear fluorescence of indium were obtained by Collins and others¹⁹. [中文](#)

There is no doubt that new isomers of β -stable nuclei will be discovered, in the course of research undertaken in different laboratories; systematic research on the radiations emitted by metastable states will certainly be very useful for the understanding of nuclear isomerism. [中文](#)

In conclusion, we may remark that it is very probable, on account of the great number of known isomers, that the radiative transitions of life-times between, say, 10^{-7} sec. and 1 sec. are much more frequent than is generally supposed. These transitions, on the other hand, are strongly converted⁶. We would expect²⁰, consequently, that *transitions of this kind, with conversion coefficients approximately 1, may be found frequently*. [中文](#)

Indeed, in the radiation emitted in the capture of slow neutrons by gadolinium, a strong component of soft electrons has been observed by Amaldi and Rasetti²¹ (life-time less than 10^{-3} sec.). Soft electronic components have also been observed in the capture of slow neutrons by other nuclei²². On the other hand, these strongly converted transitions may play a considerable part in the interpretation of γ - and X-spectra emitted by certain natural radio-elements²⁰. 中文

(144, 212-213; 1939)

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References:

1. Soddy, *Proc. Roy. Inst.*, **22**, 117 (1917).
2. Hahn, *Ber. dtsh. Chem. Ges.*, B, **54**, 1131 (1921).
3. Kourtchatow, Myssowsky, Roussinow, *C.R.*, **200**, 1201 (1935). Amaldi, d'Agostino, Fermi, Pontecorvo, Segré, *Ric. Scient.*, **6**, 581 (1935). Amaldi and Fermi, *Phys. Rev.*, **50**, 899 (1936). Bothe and Gentner, *Z. Phys.*, **106**, 236 (1937).
4. Weiszäcker, *Naturwiss.*, **24**, 813(1936).
5. Pontecorvo, *Congrès du Palais de la Decouverte*, Paris, 1937, p. 118.
6. Hebb and Uhlenbeck, *Physica*, **5**, 605 (1938). Dancoff and Morrison, *Phys. Rev.*, **55**, 122 (1939).
7. Pontecorvo, *Phys. Rev.*, **54**, 542 (1938).
8. Valley and McCreary, *Phys. Rev.*, **55**, 666 (1939). Siday, *Nature*, **143**, 681 (1939).
9. Seaborg and Segré, *Phys. Rev.*, **55**, 808 (1939). Kalbfell, *Phys. Rev.*, **54**, 543 (1938).
10. Alvarez, *Phys. Rev.*, **54**, 486 (1938). Roussinow, Yusephovitch, *Phys. Rev.*, **55**, 979 (1939). Siday, ref. 8. Walke, Williams and Evans, *Proc. Roy. Soc., A*, **171**, 360 (1939).
11. Segré, Halford and Seaborg, *Phys. Rev.*, **55**, 321 (1939).
12. De Vault and Libby, *Phys. Rev.*, **55**, 322 (1939). Le Roux, Lu and Sugden, *Nature*, **143**, 517 (1939). Seaborg and Kennedy, *Phys. Rev.*, **55**, 410 (1939).
13. Dodé and Pontecorvo, *C.R.*, **207**, 287 (1938).
14. Goldhaber, Hill and Szilard, *Phys. Rev.*, **55**, 46 (1939).
15. Barnes and Aradine, *Phys. Rev.*, **55**, 50(1939).
16. Weisskopf, *Phys. Rev.*, **53**, 1018 (1938).
17. Delsasso, Ridenour, Sherr and White, *Phys. Rev.*, **55**, 113.
18. Pontecorvo and Lazard, *C.R.*, **208**, 99(1939).
19. Collins, Waldman, Stubblefield and Goldhaber, *Phys. Rev.*, **55**, 507 (1939).
20. Pontecorvo, *C.R.*, **207**, 230 (1938).
21. Amaldi and Rasetti, *Ric. Scient.*, **10**, 115 (1939).
22. Hoffman and Bacher, *Phys. Rev.*, **54**, 644 (1938). Pontecorvo, *C.R.*, **207**, 856 (1938).

* Note added in proof. A similar conclusion was independently obtained by Roussinow and Yusephovitch [*C. R. Acad. Sci. U.R.S.S.*, **20**, 9 (1938)] who observed a soft electron radiation in the case of isomeric forms of radio-bromine.

核同质异能性的最新实验结果

庞蒂科夫

两个原子核可以具有相同的物理组成和质量但却有不同的放射性质，这一想法最初是由放射性研究的开拓者之一——弗雷德里克·索迪于1917年提出的。这一观点还可以理解为，同质异能核衰变的方式不止一种。随着人工放射性的发现，同质异能核变得更为普遍。布鲁诺·庞蒂科夫对同质异能核进行了一番专门研究，并在第二次世界大战前几个月发表了这篇关于同质异能核性质的文章，1940年他从法国移居英国。 [英文](#)

原子序数和质量数都相同的两个原子核却可能具有不同的放射性质（即核同质异能性的假说），这一假说最早是由索迪^[1]于1917年提出的。1921年，哈恩^[2]发现了铀Z；通过对该元素化学性质和放射性质的研究，哈恩推测铀Z与铀X₂是同质异能核。最近，费瑟和布雷切尔重新提出了铀Z的问题（《皇家学会会刊》，第165卷，第542页，1938年）。值得人们注意的是，很多年以来铀Z和铀X₂是仅有的已经知道的两同质异能核。 [英文](#)

发现人工放射性以后，科研工作者在对人工放射性元素的研究过程中积累的大量实验材料为同质异能现象的研究起到了相当大的推动作用。通过研究（慢和快）中子和高能 γ 射线轰击溴所产生的放射性可为人工放射性元素的领域中增添一个质量数为80的新元素，该元素也是首次得到的确定的两同质异能核^[3]。 [英文](#)

于是，随着关于人工放射性元素实验材料的增加，已确定为两同质异能核的数目大量增加，以至于我在此处不能一一引述所有关于这一问题的已发表的研究结果。目前已知道超过30对这样的核，并且毫无疑问的是，尚未发现的两同质异能核对比这数目要多得多。现在我们可以说，

核的同质异能性绝对不是一种个别现象。 [英文](#)

我们可以很自然地想到，两个同质异能核之间的物理差异与相同原子核的两个不同激发态有关（比如说基态和第一激发态）。但是，在这种情况下，高能态是如何成为亚稳态的，或者说，它怎么能维持这么长时间（在某些情况下甚至超过一天）呢？是什么机制使它们免于在很短时间内通过发射电磁辐射而崩溃呢？魏茨克回答了上述问题^[4]。 [英文](#)

根据魏茨克的假说，核的同质异能现象可以这样解释：即假定核的最低激发态具有与基态相差若干单位的角动量。这样，根据选择规则，原子核在单位时间内从上述激发态跃迁到基态的概率就会明显减少。当然，能够检验魏茨克假说真实性的实验才是最令人感兴趣的。 [英文](#)

最重要的问题之一是，对于在从一种同质异能态到另一种同质异能态的跃迁过程中最终发射出的 γ 辐射的研究。我之所以要说“最终发射”，是因为原子核具有放射性，相应于同质异能形式之一的较高能态可能会被一次普通的 β 跃迁破坏。 γ 射线- β 射线分支比将取决于两种衰变方式的相对寿命。虽然最初观测这种 γ 辐射的研究未能成功，不过值得注意的是^[5]，探测这种辐射时所遇到的相当大的困难可能是因为同质异能核之间的跃迁可以发生强烈的转换，即在这种情况下，发射出来的是低能电子而不是 γ 射线。 [英文](#)

关于在同质异能态之间的跃迁过程中发射出的辐射的内转换问题，赫布与乌伦贝克，以及丹克夫与莫里森给出了非常完整的理论^[6]，该理论指出，这些辐射必须具有接近于1的内转换系数。这些计算都是基于魏茨克的假说，因此可以得出下面的结论：如果能够找到证明其所涉及的内转换系数的确很高的实验，就在一定程度上意味着魏茨克的假说是正确的。 [英文](#)

确实，庞蒂科夫^[7]在研究放射性铯时曾观测到低能电子辐射，他将其解释为原子核从亚稳态跃迁到基态时发射出来的电子线。* [英文](#)

在近期的大量实验之后，人们目前对于这些跃迁普遍发生强烈转换这一事实再没有任何怀疑。特别是在放射性溴^[8]和43号元素^[9]的同质异

能核的实验研究中，人们已经在威尔逊云室和磁谱仪中拍下了转换电子的强线的照片。当然，内转换伴随着X射线的发射，因此，通常情况下在解释上述现象时^[9,10]，对X射线的分析就是极其重要的检验标准。

英文

寻找同种原子核（ β 放射性）的同质异能态之间可能具有的遗传关系是很有意思的：在这个研究方向上，塞格雷、哈尔福德和西博格曾描述过一种极为出色的方法^[11]，他们成功地将放射性溴的两种同质异能形式彼此分离开来。他们所用方法的原理是，假定所要研究其同质异能状态的元素能够形成某些适用于齐拉特-查默斯富集方法的化合物。当处在较高能态的同质异能核衰变到较低能态时，就会放射出 γ 射线，而由此引起的反冲作用可能足以将衰变后的原子撞出化合物。于是就可以分离出子体放射性，如同在齐拉特-查默斯方法所描述的那样。

英文

于是，这种已经成功应用于若干实例^[12]的方法就可以用于：（a）分离某些研究中的已知同质异能核；（b）在人工放射性研究中，发现未知的同质异能核的存在。

英文

此外，这种方法对于同质异能态之间的跃迁发生强烈转换这一事实给出了一个令人惊奇的新证据：实际上，由于 γ 辐射而产生的反冲是不足以将衰变后的原子撞出化合物的，但是转换电子引起的反冲却能够做到这一点。

英文

到目前为止我们讨论了放射性的同质异能素：在这些情况下出现的同质异能现象意味着同质异能素寿命之间的差异。庞蒂科夫^[5]已经注意到，具有亚稳激发态的 β 稳定核应该不是很稀有，并且，对这种亚稳态所发射的辐射进行研究应该会有助于对它的了解。这些核对于理解核的同质异能现象是有帮助的，因为对应于从一个同质异能态到另一个同质异能态的跃迁的辐射并没有受到 β 射线或 γ 射线的干扰。在经过一次核嬗变或者一次放射性衰变之后，可能会得到一个处于亚稳态的 β 稳定核。

英文

多德和庞蒂科夫^[13]通过用快中子轰击镅的方法获得了一种放射性（ $T = 50$ 分钟），化学证据表明这种放射性源自镅的一种同位素。另

外，无疑同时发生了单纯的中子俘获反应或者 $(n, 2n)$ 反应。他们将镅（50分钟）发射的软辐射解释为镅的一种同位素的某一亚稳态的辐射；事实上，对具有相当可观截面（大约为 $10 \cdot 10^{-24}$ 平方厘米）的不伴随快中子俘获的 (n, n) 激发反应，激发的那部分核落入亚稳态是可能的。

[英文](#)

塞格雷和西博格^[9]曾观测到43号元素的亚稳态，它以6小时的周期衰变（只有电子的线型能谱）到基态，基态是稳定的，或者可能具有长寿命的放射性。因此，周期为6小时的放射性是一种 β 放射性钼的子体。

[英文](#)

戈德哈伯、齐拉特和希尔^[14]曾观测到一种非常有趣的情况，并对其进行了充分的研究。他们通过上面提到的 (n, n) 反应得到了 ^{115}In 的一个半衰期为4.1小时的亚稳态（ $^{115}\text{In}^*$ ），此外，一种放射性镅（ $T = 2.5$ 天）衰变后也能得到同样的态。 $^{115}\text{In}^*$ 发射出的辐射还没被充分的研究；它的性质对理解核的同质异能现象与同量异位对来说都是非常重要的。实际上， ^{115}In 与 ^{115}Sn 是稳定的相邻同量异位核的罕见实例之一： $^{115}\text{In}^*$ 可以衰变成 ^{115}Sn （ β 辐射），或者衰变成 ^{115}In ，或者同时衰变成这两种元素。

[英文](#)

巴恩斯与阿拉丁^[15]通过用5.8兆电子伏的质子照射铟元素（反应 p, p ），也得到了 ^{115}In 的同一亚稳态。不过，我们目前仍不清楚，核激发机制是否如魏斯科普夫所讨论的那样，是由质子电场的作用而导致的激发^[16]。

[英文](#)

在上述各情况以及一些更为近期的研究^[17]中，稳定同位素的亚稳态都是通过核嬗变得到的。

[英文](#)

拉扎德和庞蒂科夫^[18]尝试了一种新方法，该方法使核嬗变不可能发生从而获得人工放射性元素，而人工放射性元素的出现有可能干扰实验研究。

[英文](#)

这种方法要使用具有连续谱的X射线照射靶子，所用X射线的能量低于核的离解能。假定被照射的核具有一个亚稳态；X射线可以激发核的较高能级；由此而被激发的一部分核就可能落入亚稳态，可以观测到的

正是来自这个态的辐射。所用连续谱的最大能量为1,850千电子伏，铀原子产生了周期约为4小时的放射性，这一放射性显然是来自我们曾提到过的 $^{115}\text{In}^*$ 亚稳态。柯林斯与其他一些研究人员^[19]从铀的稳定核荧光现象上得到了类似结果。 英文

毫无疑问，在不同实验室所进行的研究工作中，一定会发现 β 稳定核的新同质异能素；关于亚稳态发射辐射的系统性研究对于理解核同质异能现象无疑是大有助益的。 英文

总而言之，根据大量已知的同质异能素，我们可以说，具有介于诸如寿命在 10^{-7} 秒到1秒之间的放射性跃迁，很有可能比我们一般所认为的更为频繁。另一方面，这些跃迁发生了强烈的转换^[6]。由此，我们预期^[20]会频繁地发现这种转换系数近乎1的跃迁。 英文

实际上，在钷俘获慢中子的过程所发出的辐射中，阿马尔迪和拉塞蒂^[21]已经观测到了强的软电子成分（寿命不足 10^{-3} 秒）。在其他核的慢中子俘获过程中也观测到了软电子成分^[22]。此外，这些强烈转换的跃迁对于解释某些天然放射性元素发射的 γ 光谱和X光谱可能也会起到相当重要的作用^[20]。 英文

（王耀杨 翻译；厉光烈 审稿）

* 附加说明：卢西诺和约瑟夫维奇独立地得到了一个类似的结论[《苏联科学院院刊》20, 9(1938)]，他们在研究放射性溴的同质异能现象时观测到了软性电子辐射。

Cosmic Ray Ionization Bursts

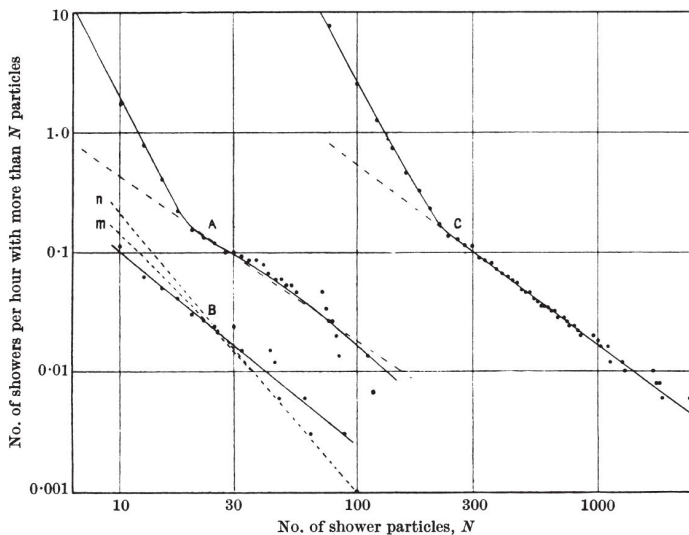
H. Carmichael and C. N. Chou

Since the beginning of the twentieth century, the study of cosmic rays had preoccupied a great many physicists for a number of reasons. First, they appeared to consist of fast-moving particles whose identity was for a long time unknown. The energy of these particles was much higher than could be created artificially in the laboratory, and they seemed to offer clues to the nature of phenomena and matter at great distances in the Universe. This paper is based on observations carried out under 30 metres of London clay on the disused part of a platform in Holborn Station on London's Underground railway network. The object of the experiment was to measure the numbers of showers of cosmic-ray particles created within electrically sensitive ionization chambers. Curve *C* represents the results of an experiment at the surface of the Earth, *A* an experiment running for 150 hours at the Underground station itself and *B* an experiment lasting 350 hours. The bends in the experimental curves *A* and *C* are taken to indicate a change in the mechanism of the production of showers of cosmic-ray particles. 中文

COSMIC ray ionization bursts produced by showers of ten or more particles in a small ionization chamber (volume 1 litre) have been recorded at sea-level in Cambridge and, thanks to the hospitality of Prof. P. M. S. Blackett and Dr. H. J. J. Braddick, under 30 m. of clay in

London. The data discussed here, curves *A* (150 hours) and *B* (350 hours), are from runs with no lead or other dense shower-producing material above the chamber (the wall of the chamber was of duralumin, 1.2 cm. thick, so as to avoid as much as possible showers produced by cascade multiplication in the chamber itself). Curve *C* (500 hours) is the result of similar observations at sea-level with a large ionization chamber (volume 175 litres, wall-thickness 0.3 cm. of steel), most of which were published by one of us¹ in 1936, when the method of recording was also described. The curves show the number of showers per hour in which N or more particles intersected the ionization chamber; the number of shower particles N was estimated on the basis of a specific ionization in normal argon of 90 ion-pairs per cm. 中文

The ionization bursts obtained at sea-level with the big ionization chamber (curve *C*) involve much larger numbers of shower particles than those obtained with the small chamber (curve *A*), and also each curve has a remarkable change of slope at a rate of occurrence about 0.16 per hour. The curves, however, can be superposed fairly closely if the size of the showers in the small chamber is multiplied by 10. We deduce from this approximate proportionality of the *size* of these showers (as distinct from their rate of occurrence) to the areas of the thin-walled chambers used to observe them that they are mostly *extensive showers*, originating in the atmosphere, of the same type as those found by Auger and his co-workers² with counters. We should not expect to find exactly the ratio of the areas (approximately 1:30) because narrow showers or condensations of rays of cross-section smaller than the area of the large chamber tend to increase disproportionately the bursts in the small chamber. 中文



中文

The bursts which are found underground (curve *B*) must be produced by the penetrating component of the cosmic rays. We have calculated the distribution curve to be expected in the tube station for cascade showers produced by electrons “knocked on” by mesons using the data given in the paper by Bhabha⁴ in which, however, the meson was

assumed to have spin $\frac{1}{2}$. We adopted, following Euler and Heisenberg³, an exponent 1.87 for the integral energy distribution of the mesons originating in the atmosphere. The calculation shows (curve *m*) that the showers resulting from this process alone are nearly sufficient to account for the bursts recorded underground, if we assume that the cross-sectional area of the showers underground is not much greater than the area of the chamber (actually more of the larger bursts are found than are given by this calculation, but the theoretical implications of this discrepancy will be discussed later).

中文

At sea-level a similar calculation (curve *n*) gives much fewer bursts than are observed even if we suppose that the showers are so narrow that all the shower particles in any one burst can intersect the small

chamber: but we already know that most of the showers observed at sea-level are at least wider than the large chamber. We therefore conclude that a negligible number of the extensive showers observed at sea-level is produced by electrons knocked-on by mesons. It would seem also that an insufficient number of such showers can be produced by the spontaneous decay of the meson, a process which might be invoked to explain the steeper parts of the sea-level curves.

中文

We think, therefore, that nearly all the showers which produce bursts at sea-level in our thin-walled ionization chambers originate very high in the atmosphere, and that the dual nature of the distribution curve at sea-level (as indicated by the change of slope) is due, not to the existence of showers of two kinds, but to the fact (already noted by Auger²) that each extensive shower has a core of closely spaced particles surrounded by a relatively wide fringe of much more thinly spaced particles able to produce bursts of small size. 中文

(144, 325-326; 1939)

Hugh Carmichael: St. John's College, Cambridge.

Chang-Ning Chou: Cavendish Laboratory, Cambridge.

References:

1. Carmichael, *Proc. Roy. Soc., A*, **154**, 223 (1936).
2. Auger, Maze, Ehrenfest and Freon, *J. Phys. et Rad.*, **10**, 39(1939).
3. Euler and Heisenberg, *Er. exak. Naturwiss.*, **17**, 1 (1938).
4. Bhabha, *Proc. Roy. Soc., A*, **164**, 257 (1938).

宇宙射线的“电离暴”

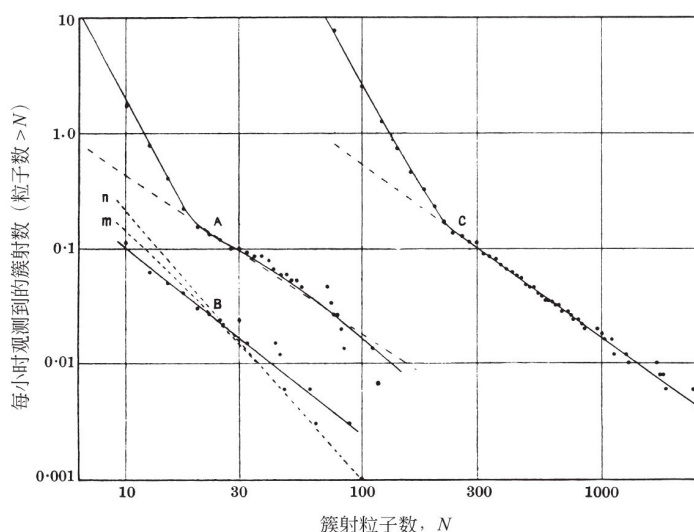
卡迈克尔，周长宁

从20世纪初开始，由于各种原因，很多物理学家都对宇宙射线的研究给予了关注。首先，它们似乎是由快速运动的粒子组成，但究竟是什么粒子，这在很长一段时间里都是未知的。这些粒子的能量大大地超过了在实验室里人工所能产生出来的能量，并且它们似乎能够为宇宙中远距离的现象和物质性质的研究提供线索。本论文是基于伦敦地面以下30米处的观察结果，该地是伦敦地铁网络霍尔本车站一个废弃不用的站台。实验的目的是采用对电荷灵敏的电离室测量宇宙射线粒子簇射的数目。C曲线代表地球表面的实验结果，A曲线代表一个在地下车站为时150个小时的实验结果，B曲线代表为时350小时的实验。A和C实验结果曲线的弯曲则用来显示宇宙射线粒子簇射产生机制的变化。 [英文](#)

把一个小电离室（容量为1升）放在剑桥的海平面上，对其中10个或更多粒子的簇射产生的宇宙射线电离暴进行了记录，并且多亏了布莱克特教授和布拉迪克博士的热心帮助，我们在伦敦地面以下30米的地方也完成了同样的实验。在本文要讨论的数据中，A曲线（150小时）和B曲线（350小时）是在小电离室上部没有覆盖铅或者其他密度较大的引发簇射的物质时得到的（电离室内壁由硬铝制造，厚1.2厘米，以尽可能避免在电离室内由连续倍增效应产生的簇射）。C曲线（500小时）是我们在海平面上用大电离室（容量为175升，壁厚0.3厘米，钢制）重复类似实验得到的结果，我们中的一人^[1]已于1936年发表了大部分数据，当时他也描述了记录的方法。从这些曲线中可以得到每小时的簇射数量，即有 N 个或是更多的粒子横穿电离室；簇射粒子数 N 是在每厘米90个离子对的普通氩气的特定离子化过程中得到的。 [英文](#)

在海平面上的大电离室观察到的离子爆发过程（C曲线）所产生的簇射粒子数量要比在小电离室里（A曲线）看到的数量多很多，而这两条曲线的斜率都在每小时观测到的簇射线为0.16处出现明显变化。如果将小电离室里的簇射量大小乘以10，那么A曲线和C曲线会很好地重叠在一起。我们根据簇射量（这一点可以从发生率中很明显地看到）与所用薄壁电离室的横截面积大致成正比这一现象可以推断出，所发生的簇射多半是广延簇射，它们产生于空气中并且与俄歇及其同事^[2]用计数器测量到的簇射属于同一类型。我们不能指望由此得到精确的面积之比（大约是1：30），因为当窄簇射或射线凝聚效应的横截面比大电离室的面积小时更容易引起非均匀的离子爆发。

英文



英文

在地面以下测量到的爆发（B曲线）肯定是由穿越了的宇宙射线产生的。利用霍米·巴巴^[4]在其论文里给出的数据，假设介子的自旋为 $\frac{1}{2}$ ，我们已经计算出由电子被介子撞击而产生的级联簇射在地铁站里的预期曲线分布。根据欧拉和海森堡^[3]的方法，我们认为大气中介子累积能量分布曲线的指数为1.87。如果我们假设在地面以下的实验中，簇射区域的横截面不比电离室大多少，那么从计算结果中可以看到（m曲线）：仅由介子和电子的碰撞过程所产生的簇射就足以解释在地面以下记录的爆发了（实际上测量到的大型爆发数值要多于计算值，对这种差异的理

论解释将在以后讨论)。

英文

在海平面上用上述方法得到的计算值(n 曲线)比观察到爆发的数值低很多,即使我们假设簇射范围非常窄,以至于每次爆发中的所有簇射粒子都能够横穿小电离室,但事实上我们已经知道,在海平面上所观察到的大部分簇射范围至少都比大电离室的范围大。因此,我们得出结论:在海平面上所观察到的少量爆发簇射是由介子撞击电子产生的。这种簇射的量不够大,可能是由介子的自发衰退造成的,这也许可以作为由海平面上的观测数据得到的 n 曲线有一个斜率较大的部分的原因。

英文

因此,我们认为,几乎所有能在位于海平面上的薄壁电离室内产生爆发的簇射都来自于大气层中非常高的地方,而海平面上分布曲线所表现出的双重特性(由斜率的变化可以看出)并不是由于存在两类簇射,而是由于以下原因(这一点俄歇^[2]也注意到了),即每次爆发簇射都有一个由密排粒子组成的核心,其周围是由排列非常松散的粒子组成的广大边界地区,而在这些边界地区就会产生规模较小的爆发。

英文

(李忠伟 翻译;马宇 审稿)

Measurements of the Velocity of Light

Commenting on the earlier proposal of M. E. J. Gheury de Bray, Lord Kitchener asserted that observations suggesting a very slight slowing of the speed of light over time were probably due to error. Here Gheury de Bray responds. Although some techniques for measuring the speed of light could be criticized, he says, this cannot be said of his toothed-wheel method. He also notes that Simon Newcomb and Albert Michelson had independently reported similar results, which differed by just the amount expected if the speed of light were slowly changing. All the same, there seems now no evidence of such an effect, although the possibility of changes in physical constants over time is still debated. [中文](#)

M. E. J. Gheury de Bray suggests¹ that measurements of the velocity of light show that it is changing according to a formula:

$$c = 299,900 - 3.855 T \quad (1)$$

T being measured in years from 1900. [中文](#)

Assuming that Planck's constant and the energy E given out by an excited atom remain unchanged, the relation

$$E\lambda = ch$$

(2)

shows that a change in c must be accompanied by a proportional change in λ . But the wave-length of the red calcium line has remained constant to within one part in five million for thirty years, only 0.5 percent of the change required by (1). [中文](#)

It is probable that there are unsuspected systematic errors in the determinations of c .

Kitchener [中文](#)

* * *

The decrease of velocity of light deduced from the red-shifts is of the order of 1 km./sec. in 6,000 years, or 1 in 600,000,000 for thirty years, which is quite consistent with the apparent constancy of the wave-length mentioned by Lord Kitchener. Our observations, being affected by unsuspected systematic errors, and covering only a third of a century, give what is probably a greatly exaggerated rate of slowing down. The remarkable fact is that *all* the determinations are unanimous in indicating the existence of such a variation, and the red-shifts, if interpreted so as to escape from fantastic results, confirm it.

[中文](#)

The Table 1 of the communication referred to cannot be dismissed on the ground of “unsuspected systematic errors”. It is admitted that the method of the revolving mirror may suffer from physical bias, but no such reproach can be levelled against the toothed wheel method, which is only open to objections of a physiological nature. These can be readily overcome by substituting for the observer’s eye a photo-electric sensitive device. While France and the United States share between them practically the whole initiative in the measurement of c , Great Britain has only to her credit a conspicuous failure. Is there in

this country no one who can redeem it from this position and settle this question, which lies at the basis of physical science, considered in its broadest aspect? [中文](#)

Two observations, of Newcomb (1882.7:299,860) and of Michelson (1882.8:299,853) agree so closely that, if we consider that they were made by different observers, working independently with different instruments and different techniques, in different places, they must be extremely accurate, despite their large probable errors. It is significant that the second in date gives a lesser value of c . [中文](#)

M. E. J. Gheury de Bray

(144, 945; 1939)

Kitchener: Trinity College, Cambridge.

M. E. J. Gheury de Bray: 49, Great Thrift, Petts Wood, Nov. 2.

Reference:

1. *Nature*, **144**, 285 (1939).

光速的测定

基奇纳勋爵在评论谷瑞·德布雷早前的猜想时断言，观测结果所显示的光速随时间的轻微变慢很可能是由于误差造成的。谷瑞·德布雷在这篇文章中予以回应。他说，尽管测量光速所用的一些技术值得怀疑，但他所使用的齿轮方法不在此列。他也指出西蒙·纽科姆和阿尔伯特·迈克尔逊都曾独立地报道过类似的结果，区别仅仅在于光速减慢的变化速率不同。尽管如此现在看来似乎仍没有证据支持这个效应的存在，虽然对物理常数随时间变化的可能性仍然在探讨之中。

[英文](#)

谷瑞·德布雷指出^[1]，光速的测定结果表明它依照如下公式而变化：

$$c = 299,900 - 3.855 T \quad (1)$$

式中的 T 是自1900年以来的年份。 [英文](#)

假定普朗克常数和受激发原子释放出的能量 E 保持恒定，则关系

$$E\lambda = ch \quad (2)$$

表明光速 c 变化的同时必定伴随着 λ 与之成比例的变化。但是我们观测到红色钙谱线的波长在30年中的变化小于五百万分之一，而这只有公式(1)中变化量的0.5%。 [英文](#)

这可能是在光速 c 的测量过程中存在的未知的系统误差。

根据红移推断，光速在6,000年中降低了1千米/秒的数量级，或者说在30年中降低了1/600,000,000，这与基奇纳勋爵所谈到的波长的表观不变性颇为一致。由于受未知的系统误差的影响，以及观测仅持续了1/3个世纪，所以我们观测到的结果很可能远远夸大了光速减慢的速率。不过显而易见的是，所有测量结果都一致地表明这种变化的存在，而且，如果不对红移进行荒诞怪异的解释的话，那么红移就证实了这一点。

[英文](#)

不能由于存在“未知的系统误差”而把我之前提到的表1（见本书第689页）排除在考虑的范围之外。我们知道，旋转镜方法可能会受到物理偏置的影响，但是齿轮方法就没有受到这类影响，这种齿轮方法存在的唯一问题是研究者的生理特征的影响。不过通过用光电敏感装置代替观测者的眼睛，我们就可以很容易地克服这些困难。实际上，当法国和美国共同占据了测定光速 c 值的全部主动性时，留给英国的只是赤裸裸的失败。难道这个国家就没有人能挽回这种局面并且从最广泛的视角来解决这个物理科学的基础问题吗？

[英文](#)

纽科姆（1882.7：299,860）和迈克尔逊（1882.8：299,853）的观测结果惊人一致，如果考虑到它们是由不同的观测者用不同的装置和技术方法在不同的地点各自独立地得到的，我们甚至可以断言这些结果是极为精确的，哪怕存在着较大的或然误差。重要的是，观测日期靠后的迈克尔逊给出了较小的 c 值。

[英文](#)

谷瑞 德布雷

（王耀杨 翻译；张元仲 审稿）

The Evolution of the Stars

F. Hoyle and R. A. Lyttleton

Astronomers Fred Hoyle and Raymond Lyttleton review how recent advances in nuclear theory were fundamentally changing astronomers' understanding of stellar evolution. It was now possible, as George Gamow had recently argued, to probe the nuclear chemistry likely to be important at the densities and temperatures prevailing in stars. But Hoyle and Lyttleton think Gamow went rather too far in suggesting most problems of stellar evolution were now solved. In Gamow's view, for example, all red giant stars must be of very recent origin, which seemed most unlikely. Hoyle and Lyttleton were correct: physicists then understood only the rudiments of nuclear chemistry, and knew nothing of nuclear fusion, a key process driving all stellar activity and evolution. [中文](#)

PROF. G. Gamow has recently discussed in *Nature*¹ the consequences of recent developments in nuclear theory on the problem of stellar evolution. In the light of the exact knowledge that is now available of a large number of nuclear reactions, it is possible to decide which processes rise to importance at the densities and temperatures prevailing in the stars, and on this basis trustworthy estimates have been given for the rate of liberation of subatomic energy. These results, which are the outcome of laboratory investigations, furnish the mathematical theory of internal constitution of the stars with a

new equation that enables the luminosity of a star to be calculated by direct methods. The information so obtained has been utilized to attempt to resolve the many paradoxes and discrepancies encountered in discussing the general problem of stellar evolution. All this recent work has been authoritatively summarized by Gamow with great clarity and understanding in the article referred to above. It is therefore with some surprise that we find that Prof. Gamow concludes his article with the impression that these new developments practically solve the problems of stellar evolution. This seems to us to be so far from being the case that some further discussion of the claims of nuclear theory as the main factor in stellar evolution would be desirable. [中文](#)

In the first place, it should be noticed that the application of nuclear theory in its present state inevitably leads to a result at least as embarrassing as any of the questions that it might possibly resolve. For the theory maintains that no synthesis of atomic nuclei from hydrogen is possible within the stars except for the very light elements. This would imply that the stars can no longer be regarded as the building place of the heavy elements, which must have formed before they became part of the star—if indeed they ever were formed. Now although such a conclusion does not itself constitute a logical contradiction, it seems to us to present such overwhelming difficulty that it is much more reasonable to conclude that the basis of nuclear theory is in need of revision rather than that the heavy elements were not formed by synthesis. On the other hand, many investigators seem to have accepted the former result as satisfactory, and in particular Gamow has proceeded to make it the basis of a theory of the red giant stars. [中文](#)

Secondly, Prof. Gamow apparently regards the conclusion that various classes of stars should be of totally different ages as a natural one. Thus the fact that the present theory leads to a life-time for certain

massive stars of order 10^{-3} the life-time of the Sun is not regarded as a difficulty at all; indeed it is merely supposed that this is the case and the theory remains unquestioned. In point of fact, it is an essential part of the theory as proposed by Gamow that all red giant stars are considered as of very recent formation, since the presence of lithium, etc., is required to enable them to radiate with their supposed low internal temperatures. [中文](#)

Now if all the stars could be regarded as single autonomous bodies, it would be difficult to dispute the validity of these views by direct means. But it so happens that the frequent occurrence of binary systems enables a simple test of the theory to be made, for in the case of binary stars both components must be of comparable age. It is immediately clear that the well-known difficulty concerning the relative emission per unit mass of the components of doublestars must remain in any theory that appeals only to the internal properties of the stars, although by making very artificial assumptions in Gamow's theory some of these discrepancies might be avoided. For example, it would require as a general result that the less massive components of binary systems form with a hydrogen content differing systematically from that of their companions. In certain cases this would lead to even more dubious initial conditions: thus, whilst Sirius must have formed with high hydrogen content, it would have to be assumed (according to the more generally accepted theory of degenerate matter) that the companion formed almost solely from heavy elements for it to have been practically exhausted during the whole of its existence. Such a solution of this difficulty could scarcely be regarded as satisfactory even if there were no other objection to the theory described by Gamow. [中文](#)

It should be particularly noticed that the foregoing suggestion assumes that the components have not evolved by fission, for this latter process (even if it were dynamically satisfactory) would clearly lead to two

stars of closely similar compositions. We have been able to show, however, that to produce close binary systems, periods of order 5×10^{10} years are necessary². Thus the existence of spectroscopic binary systems in which one component is a red giant or any highly luminous star presents an immediate contradiction of the theory given by Gamow. Moreover, there seems to be a general tendency for the mass of binary systems to increase with decreasing separation. 中文

文

While on the subject of fission, it is perhaps only proper to point out here that although the mathematical investigations of the development of rotating fluid masses clearly demonstrate that binary stars cannot be generated by fission³, many astronomers do not yet seem to have realized the physical significance of the mathematical results. As a consequence of this there are still many who “believe” in the fission theory. But as will be seen, even an appeal to fission could not save Gamow’s theory of the red giant stars, in addition to which it would raise afresh the difficulty of the relative emissions of the components in binary stars. Even if some process of break-up of a single star led to a binary system, it is evident that the components must have similar chemical compositions, while in close binary systems consisting of a red giant star and a class *B* star, Gamow’s theory would require the red star to be the less massive component on account of the mass luminosity relation. But observation shows that in such pairs the giant star tends to be the more massive component. This is the case, for example, in the three stars υ Sagittarius, V Cephei and ζ Aurigae. Thus it seems that no matter from what angle we approach the questions raised by the observed properties of binary systems, the paradoxes already recognized by astronomers must remain in one form or another. 中文

However, quite apart from the foregoing objections to the constructive portion of Gamow’s article, it is very noticeable that no reference is

made to the wide class of dynamical features that is associated with the stars. This, of course, is the direct result of attending only to the internal physical properties of the stars; but the dynamical features we have in mind are altogether too marked to remain unaccounted for in a satisfactory theory. Thus such questions as the formation of individual stars, and of binary and multiple systems, together with the general increase of mass with decreasing separation, and the observed approximation to equipartition of energy among the stars seem to present the real key to any theory of stellar evolution. An internal theory can give no explanation for the correlation between peculiar velocity and spectral class or the observed tendency for massive stars to lie in the galactic plane, features that must be related to the previous history of the stars. [中文](#)

It has been customary during recent years for investigators on stellar evolution to devote attention to internal constitution with little or no regard for the dynamical features. It appears that Prof. Gamow has followed essentially in this tradition and therefore confined his article to the modifications effected by the introduction of modern nuclear theory. Thus, in dealing with the properties of variable stars, no attempt is made to account for the three distinct periodicity groups comprised by stars of periods of order half a day, four days and 300 days. These variables also show a marked preference as regards spectral class, the first being largely of classes *B* and *A*, the second of *F* and *G* and the third of class *M*. Moreover, the two short-period groups exhibit a most remarkable property in that none of them, out of more than two hundred available examples, possesses a close companion, whereas about one star in five of normal stars of similar spectral classes does possess a close companion. On the other hand, long-period variables appear to possess a normal complement of companions. The first and third types are stars of moderate luminosity and show no pronounced galactic concentration, whereas the variables of intermediate period, the Cepheids, are strongly

concentrated to the galactic plane and are among the most luminous known stars. Thus it is clear that very remarkable dynamical properties are intimately connected with even the different types of variability, and therefore that purely internal considerations are most unlikely to prove capable of elucidating the nature of the connexion.

[中文](#)

From these and many other dynamical qualities associated with various types of stars, it appears to us that Prof. Gamow has over-estimated the importance of nuclear theory in the problem of stellar evolution. Indeed, in our opinion nuclear physics has very little to add to the results already conjectured by astrophysicists, and can merely serve to confirm these conjectures, a typical instance being the mass-luminosity relation itself. Finally, we wish to point out that although the present article consists largely of criticism, we have discussed elsewhere a number of the questions raised², and it has been found that purely dynamical considerations may be sufficient to provide a natural explanation of many of the difficulties mentioned in this article. [中文](#)

(144, 1019-1020; 1939)

F. Hoyle and R. A. Lyttleton: St. John's College, Cambridge.

References:

1. *Nature*, **144**, 575, 620 (Sept. 30 and Oct. 7, 1939).
2. *Proc. Camb. Phil. Soc.*, (4), **35** (1939).
3. *Mon. Not. Roy. Astr. Soc.*, **98**, 646 (1938).

恒星的演化

霍伊尔，利特尔顿

天文学家弗雷德·霍伊尔和雷蒙德·利特尔顿回顾了核物理理论的近期进展是如何从根本上改变天文学家对恒星演化的理解的。如乔治·伽莫夫近期所指出的，现在有可能证明核化学在恒星当时的密度和温度下是有重要作用的。伽莫夫认为恒星演化的大多数问题现在都已经解决了，但霍伊尔和利特尔顿对此并不认同。例如，伽莫夫认为所有红巨星一定是在新近才产生的，但这似乎是最不可能的事情。霍伊尔和利特尔顿是对的：那时的大多数物理学家只知道核化学方面的初级知识，但对核聚变这一驱动恒星活动和演化的关键过程却一无所知。 [英文](#)

乔治·伽莫夫教授最近在《自然》^[1]杂志上讨论了核物理理论的最新进展在恒星演化问题上所取得的结果。根据现有可用大量核反应得到的准确知识，人们有可能确定在恒星当时密度和温度下哪些过程具有重要的作用，并且在此基础上，人们得到了对亚原子能量释放率的可靠估计。这些实验研究得到的结果为计算恒星内部结构的数学理论提供了一个新的方程，由此可以采用直接的方法计算恒星的光度。我们利用所获得的信息尝试解决恒星演化的普遍问题中遇到的许多矛盾和差异。在上面所引用的那篇文章中，伽莫夫以十分清晰易懂的方式对近来的所有工作进行了权威性的总结。令人有些惊讶的是伽莫夫教授在他的文章中得出的结论给人这样的印象：这些新的进展从实际上解决了恒星演化的多种问题。而在我们看来情况远非如此，核物理理论在恒星演化中作为主要因素的论断还需要进一步讨论。 [英文](#)

首先，我们应该注意到目前核物理理论的应用和它有可能解决的任何问题一样，会不可避免地导致一种同样令人为难的结果。因为该理论

认为，在恒星内部氢仅能合成一些非常轻的元素，而不能合成其他的原子核。这意味着恒星不能再被当成是重元素产生的地方，如果这些重元素确实曾经产生过，那么它们必须在变成恒星的一部分之前就已经产生了。现在尽管这个结论自身在逻辑上并不矛盾，但是目前在我们看来它却造成了非常巨大的困难，所以更为合理的结论是：核物理理论的基础所需要的是修正而非重元素不是由合成产生的。另一方面，许多研究者似乎已经认同前一个结论是令人满意的，特别是伽莫夫，他已着手把它作为了红巨星理论的基础。 [英文](#)

其次，伽莫夫教授显然认为各种类型的恒星有完全不同的年龄是很自然的事情。因此，由现有理论得出的某些大质量恒星的寿命仅仅是太阳寿命的 10^{-3} 倍的结论完全没有被认为是一件困难的事情；事实上大家认为这就是事实且现有理论是毋庸置疑的。其实正如伽莫夫所提出的，所有红巨星形成于最近这样一个观点是现有理论里必不可少的一部分，这是因为需要锂等元素的存在，以使其可以在假定的内部低温中发出辐射。 [英文](#)

现在，如果所有恒星都可以被看作是独立的天体，那么可能很难用直接的方法对这些观点的正确性提出质疑。但幸亏多次发现的双星系统使我们可以对该理论进行简单的检验，因为在此情况下，两颗成员星应该有同等的年龄。尽管伽莫夫理论中人为的假设避免了某些矛盾，但很显然，对于任何单纯只研究恒星内部性质的理论来说，著名的关于双星中成员星的单位质量相对辐射的困难仍然存在。例如，作为一个一般性结果人们可能会假设双星系统中质量较小的成员星在形成的时候氢含量系统性地和它们另外的成员星不同。在某些情况下，这可能会让初始条件变得更加可疑：所以，虽然天狼星在形成时氢含量可能很高，但我们不得不假设（考虑到简并态物质的理论已被更为广泛地接受了）其成员星几乎只由重元素组成，以使其在存在的整个期间耗尽主要的核燃料。即使对于伽莫夫提出的理论没有其他反对的理由，但是对于上述困难，这样的解决方案也是绝不可能令人满意的。 [英文](#)

应该特别注意，上述理论假设了成员星不是通过分裂演化而来的，因为分裂演化（尽管在动力学上是合理的）会产生两颗组分相似的恒星。然而，我们已经能够证明，必须有 5×10^{10} 年量级的时间^[2]才能产

生密近双星系统。于是分光双星中，若其中一颗成员星是红巨星或者任一颗高亮度的星，就必然同伽莫夫所提出的理论相矛盾。另外，似乎存在一个普遍趋势，即双星系统的质量随间距的减小而增加。 [英文](#)

在恒星分裂的问题上，或许在这里指出最为合适，即尽管转动流体演化的数学研究结果清楚地证明了双星不可能由分裂产生^[3]，但是许多天文学家似乎还并没有意识到这些数学结果在物理方面上的重要性。因此仍然还有很多人“相信”分裂理论。但是正如人们将要看到的，即使求助于分裂理论也不能挽救伽莫夫的红巨星理论，此外双星成员星的相对辐射问题将再次出现。就算单星分裂的某一阶段会产生双星系统，但可以肯定的是成员星之间仍应该有相似的化学组成，对于一个由一颗红巨星和一颗B型星组成的密近双星系统，伽莫夫的理论认为基于质光关系，红巨星的质量相对较小。但观测结果表明在这种双星系统中，红巨星的质量往往相对较大。例如在人马座 υ 、仙王座V V、御夫座 ζ 这三个双星系统中，情况均是如此。这样看来，似乎无论我们从什么角度来处理双星系统观测性质上的问题，这个已被天文学家意识到的矛盾总会以某种形式存在。 [英文](#)

然而，除了前面对伽莫夫文章理论构建部分提出的异议外，很明显，还没有文献提到与恒星相关的广泛动力学特征。当然，这是只关注恒星内部物理性质的直接结果；但是，总的来说我们考虑的动力学性质是个很重要的问题，为此任何一个理论要令人信服都应该对此给出说明。于是，诸如单个恒星、双星以及聚星系统的形成，双星质量普遍随间距的减小而增加，以及观测到类似在恒星之间近似均分能量，类似这样的问题似乎是所有恒星演化理论的真正关键。一个恒星内部结构的理论不能解释本动速度和光谱类型之间的关系，也不能解释为什么观测到的大质量恒星都倾向位于银道面上，而这些特征必然和恒星早先的历史有关。 [英文](#)

近年来，致力于恒星演化研究的科学家们都习惯性地只关注恒星内部组成而很少或者不关心其动力学特征。伽莫夫教授似乎也基本上遵循了这个传统，因此他的文章局限于引入现代核物理理论加以改进。因此，在处理变星性质的时候，他没有试图解释由周期为0.5天、4天和300天量级的恒星组成的三个不同的周期组。这些不同周期的变星也明

确显示出了与光谱型相关的顺序，第一类主要是B和A型星，第二类是F型星和G型星，而第三类是M型星。此外，两个短周期的组还显示出一个最显著的特性：在已有的两百多个例子中，没有一个有密近的伴星。而在具有类似光谱型的一般双星中，每5对就有一个具有密近的伴星。另一方面，长周期的变星有正常的伴星。第一类和第三类中等亮度的恒星并没有显著的向银道面聚拢，而中等周期的变星，如造父变星，却都位于已知最明亮的恒星之中并且都高度聚集在银道面上。这清晰地表示，明显的动力学性质甚至与不同类型的光变有着紧密的联系，因此只考虑恒星的内部结构是不大可能诠释这些联系的本质的。 英文

考虑到上述这些情况以及其他与各种类型恒星相联系的动力学性质，在我们看来伽莫夫教授高估了核物理理论在恒星演化问题中的重要性。事实上，我们认为核物理对天体物理学家所推测出的结果几乎没有什么补充，只能用其来验证这些推断，一个典型的例子是质光关系本身。最后，我们想指出，尽管本文主要是批评，但是我们已经在另外一篇文章中对所提出的许多问题^[2]进行了讨论，并且我们发现从纯粹的动力学角度考虑可能足以为本文中提到的这些困难提供一个合理的解释。

英文

（钱磊 翻译；何香涛 审稿）

Radioactive Gases Evolved in Uranium Fission

L. Wertenstein

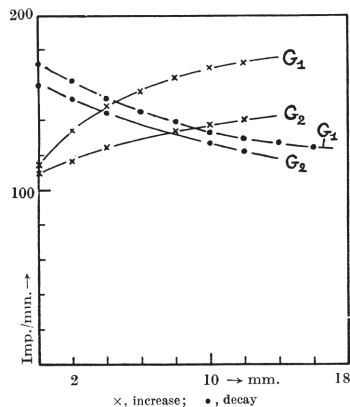
The discovery of nuclear fission and its release of enormous energy posed the possibility of putting that energy to use, either in weapons or in industry. But scientists still knew very little of many fundamental processes which might influence its successful engineering. Here physicist Ludwik Wertenstein, writing from a Poland recently occupied by Nazi Germany, reports that the fission process produces radioactive gases. He had detected the radioactivity induced into several gases circulating about a sample of uranium bombarded by neutrons, and found traces of essentially two distinct radioactive components, with half-lives of about 30 seconds and four minutes. This was merely the beginning of detailed investigation required to bring nuclear energy into engineering practice. [中文](#)

IN this letter, a brief account is given of the preliminary results of an investigation of the radioactive gases evolved in the fission of uranium nuclei. This investigation was commenced this summer but was interrupted by the outbreak of the War. Even if the results so far obtained are not more complete than those obtained in the meantime by other investigators¹, it may still be of interest to describe the method employed, which follows somewhat different lines. [中文](#)

The radioactive gases evolved in the fission process were carried by a circulating stream of an inactive gas through two Geiger-Müller counters placed in succession. The time lag of the arrival of the gas in the two counters could be varied within wide limits by means of a system of capillary glass tubes of various bores placed in parallel and fitted with stopcocks. The magnitude of the lag was ascertained by separate experiments in which actinon or thoron was circulated. As a carrier gas, acetone vapour at a pressure of 10 mm. mercury was used because of its favourable properties for the working of the counters. The circulation was kept up by means of a Vollmer glass pump. 中文

The uranium vessel, containing about 30 gm. of uranium oxide (U_2O_3), was surrounded by paraffin and provided with a well to allow introduction or removal of the neutron source, which consisted of about 30 mgm. of radon + beryllium. In the experiments, the counting rate of both counters was recorded for a period of time immediately following the commencement or cessation of irradiation. Typical results, using a time lag between the counters of 15 sec., are shown in the accompanying figure, from which it may be seen that the curves obtained for increase and for decay are almost complementary, and indicate several periods, of which some are of the order of a minute, while others are evidently much longer, giving rise to a residual activity almost constant within the time of the experiment.

中文



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The shorter periods were estimated from a decay curve obtained in a separate experiment, in which the flow of gas was stopped at the same time that the source was removed, and the records of the two counters at any subsequent time simply added. This gave two periods of about 30 sec. and 4 min., the ratio between the rates of production of the corresponding gases being estimated as 1.82. (Glasoe and Steigman (*loc. cit.*) find two gaseous products of uranium fission of periods 30 sec. and 5 min., of which the first transforms into a product of 3 min. period. It is possible that the period of 4 min. found in our experiments results from a combination of the periods 3 min. and 5 min.) 中文

A test of these estimates was further obtained by calculating from them the values of the ratio between the counting rates of the two counters for steady flow with the various circulating periods obtained by inserting different capillary tubes in the circuit, and comparing the calculated values with the values measured 12 min. after the beginning of the irradiation. This interval of time is not quite sufficient for complete equilibrium to be established, but, on the other hand, it is sufficiently short compared to the periods of the long-lived transformation products to ensure that the values obtained do not depend on the formation of these products to any appreciable extent.

Assuming that the radioactive gas consists only of the two short-period components of decay constants λ_1, λ_2 produced at the rate of n_1, n_2 atoms per sec., the counting rate in any of the counters can readily be shown to be given by

$$G = n_1 e^{-\lambda_1 \tau} \frac{1 - e^{-\lambda_1 \theta}}{1 - e^{-\lambda_1 T}} + n_2 e^{-\lambda_2 \tau} \frac{1 - e^{-\lambda_2 \theta}}{1 - e^{-\lambda_2 T}},$$

where τ is the time taken by the circulating gas to travel from the uranium container to the counter in question, θ the time taken by the gas to flow through the counter, and T the period of the whole circulation process. 中文

In the table are recorded the counting rates, G_1, G_2 , for the two counters measured 12 min. after the beginning of the irradiation for four capillary tubes corresponding to values of the time lag $\tau_2 - \tau_1$ between the counters stated in the first column. 中文

$\tau_2 - \tau_1$	G_1	G_2	$G_1 : G_2$	$(G_1 : G_2)$ calc.
15 sec.	108	63	1.72	1.31
50 sec.	94	45	2.09	2.01
2 min.	52	24	2.15	2.10
3 min.	42	21	2.00	2.01

中文

The agreement between the experimental and calculated values for the ratio $G_1 : G_2$ is seen to be very good except for the fastest circulation, for which the calculated value depends mostly on the shorter period and on the short time-lag, the determinations of which are the least precise. 中文

(144, 1045-1046; 1939)

L. Wertenstein: Mirosław Kernbaum Radiological Laboratory, Warsaw Society of Sciences, At Turczynck, near Warsaw, Sept. 24.

Reference:

1. Hahn, O., Strassmann, F., *Naturwiss.*, **27**, 163 (1939). Heyn F., Aten, A., and Bakker, C., *Nature*, **143**, 516 and **679** (1939). Glasoe and Steigman, *Phys. Rev.*, **55**, 982 (1939).

铀核裂变时放出的放射性气体

维腾斯坦

核裂变的发现及其释放的巨大能量显示了将这种能量用于武器和工业的可能性。但是科学家对它的许多基本的过程仍了解很少，这可能影响到对它的成功工程化。物理学家卢德维克·维腾斯坦从最近被纳粹德国占领的波兰写出的信中指出，裂变过程产生放射性气体。他探测到在中子轰击铀样品周围几种气体循环引入的放射性，并发现两种截然不同的放射性组分的踪迹，它们的半衰期分别为30秒钟和4分钟。这仅仅是将核能引入工程应用详细研究的必要开端。

英文

这封信对铀核裂变中放出放射性气体研究的初步结果进行了简要地说明。这项工作原计划于今年夏天开始着手，但是因二战的爆发而中断。尽管到目前为止我们所得到的结果并不比其他研究者在此期间所得到的结果^[1]更为完善，但我们采用了一种稍为不同的研究方法，而描述该方法可能也是很有趣的。

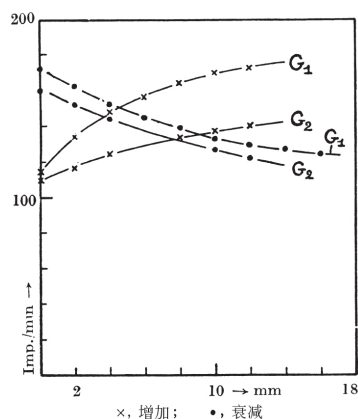
英文

裂变过程中放出的放射性气体依次流经放置好的两套盖革-米勒计数器，被其中无放射性气体环流携带出来。利用一套平行放置且装有活栓的不同孔径的毛细玻璃管构成的系统，可以对两套计数器内气体到达的时间延迟在很宽的限度内进行调节。时间延迟的长短可以通过钢射气或钍射气循环的分立实验来确定。实验中我们使用10毫米汞柱压强的丙酮作为载气，因为它具有有利于计数器正常运转的性质。气体循环是通过瓦尔莫玻璃泵来维持的。

英文

将盛有大约30克氧化铀 (U_2O_3) 的容器用石蜡包围起来，并提供一个很容易引入和取走中子源的井，中子源由大约30毫克氘和铍组成。实验过程中，在照射开始或停止之后的一段时间，记录两台计数器的计数

率。附图中显示了两计数器间的时间延迟为15秒钟时得到的典型结果，从图中我们可以看到，所得到的增长和衰减曲线几乎是互补的，并且展现出若干个周期（其中一些的数量级为分钟，另外一些则明显要长很多），这些在实验期间引起了几乎恒定的剩余放射性。 [英文](#)



[英文](#)

我们根据分立实验中得到的衰减曲线估算了较短的周期。实验中，气体的流动随着移开中子源而同时停止，在此之后对两台计数器的记录结果简单相加。这给出了约为30秒钟和4分钟的两个周期，产生相应气体的速率的比值的估算值为1.82。（格拉索和斯泰格曼（见上述参考文献）发现铀裂变的两种气体产物周期分别为30秒钟和5分钟，其中第一种转变为一种周期为3分钟的产物。我们在实验中发现的周期为4分钟的产物有可能是3分钟和5分钟周期结合的结果。） [英文](#)

对上述估算的检验可以通过如下方式获得：通过在环路中插入不同的毛细管，获得各种环流周期，对具有这些周期的稳定流动计算两台计数器计数率的比值，并将计算所得的数值与辐射开始12分钟后测得的数值相比较。这一时间间隔对于完全建立平衡来说不是很充足，不过从另一方面来说，它与长寿命衰变产物的周期相比却已足够短，这足以确定所获得的值在任何可观程度上都不依赖于这些产物的形成。 [英文](#)

假设放射性气体仅由衰变常数分别为 λ_1 和 λ_2 、生成速率分别为每秒 n_1 和 n_2 个原子的两种短周期成分组成，其任一台计数器中的计数率都可以很容易由下列式子给出：

$$G = n_1 e^{-\lambda_1 \tau} \frac{1 - e^{-\lambda_1 \theta}}{1 - e^{-\lambda_1 T}} + n_2 e^{-\lambda_2 \tau} \frac{1 - e^{-\lambda_2 \theta}}{1 - e^{-\lambda_2 T}}$$

式中， τ 表示循环气体从盛铀容器到达我们正在讨论的计数器所需的时间， θ 表示气体流过计数器所需的时间， T 表示整个循环过程的周期。

英文

下面的表格中记录了两台计数器的计数率 G_1 和 G_2 ，其中， G_1 和 G_2 是在辐照开始12分钟后，两台计数器对相应于表中第一栏所列出的两个计数器之间的时间延迟 $\tau_2 - \tau_1$ 的四个毛细管进行计数所得结果。

英文

$\tau_2 - \tau_1$	G_1	G_2	$G_1 : G_2$	$(G_1 : G_2)$ 计算值
15 秒钟	108	63	1.72	1.31
50 秒钟	94	45	2.09	2.01
2 分钟	52	24	2.15	2.10
3 分钟	42	21	2.00	2.01

英文

我们可以看到，除了对于最快的循环之外，实验值和计算值之比 $G_1 : G_2$ 符合得相当好，这是因为对于最快的循环计算值主要依赖于较短的周期和短时间延迟，所以由此确定的结果精确性最差。

英文

(王耀杨 翻译；张焕乔 审稿)

Scattering of Mesons and the Magnetic Moments of Proton and Neutron

W. Heitler

Walter Heinrich Heitler was a German scientist who had emigrated to Britain in the 1930s. The particles of matter called mesons had not been observed in practice but only their existence inferred; their role was supposed to mediate the forces between particles of nuclear matter, neutrons and protons for example. This highly technical note suggests that other properties of the nuclear particles such as their magnetic moment could be calculated from their functions as mediators of the nuclear force. [中文](#)

THE meson theory in its present form exhibits a number of difficulties which are connected with the particular way in which the conservation of charge and the spin enter the interaction between mesons and the nuclear particles. The expression for the anomalous magnetic moment of the proton and neutron¹, for example, diverges as $\int_0^{\infty} dk$. The cross-section for the scattering of mesons by a nucleus is found to be very much larger than experiments permit and increases rapidly with increasing energy. This would be incompatible with the high penetrating power of cosmic ray mesons. The cross-section for scattering of a longitudinal meson (rest mass μ) with energy ε (momentum p/c) is, according to the present theory, given by²

$$\varphi = 4\pi \left(\frac{g^2}{\mu c^2} \right)^2 \frac{p^4}{\varepsilon^2 (\mu c^2)^2} \quad (1)$$

中文

From the analogy of mesons with light quanta, one would expect a cross-section of the order $(g^2/Mc^2)^2$, where M is the mass of the proton, and no increase with energy for $\varepsilon > \mu c^2$. The experiments by J. G. Wilson³ have shown that the scattering cross-section even for an energy so low as a few times μc^2 (10^8 ev.) is smaller than (1) by an order of magnitude and does not increase with energy. 中文

As can be seen from the computation of (1), both difficulties are due to the fact that the conservation of charge forbids a number of transitions which could occur if mesons were neutral particles². A neutral meson could, for example, be *emitted and absorbed* by a proton. A positive meson can *only be emitted by a proton but not absorbed*. The cross-section for scattering would be of the right order of magnitude if we allow a positive meson also to be absorbed and a negative one to be emitted by a proton, etc., or, in other words, if “proton states” with charges $-e$ and $+2e$ existed⁴. The introduction of those particles meets, however, with the following difficulties. First, particles of this nature are not observed and are unlikely to have escaped observation if they occur in heavy nuclei. Secondly, if a proton were capable of emitting also a negative meson, the negative meson would give a contribution to the anomalous magnetic moment of the proton of opposite sign and—all other quantities being equal—of the same value as the contribution from the positive meson. Thus, there would be no anomalous magnetic moment at all. 中文

These difficulties can be overcome if we assume that the rest mass of the new particles is considerably *higher* than that of the proton, say, by 25–50 electron masses (see below). The particles would then be extremely unstable and would not play any part in the structure of heavy nuclei. Denoting the mass difference between the new particles

and the proton by ΔM , the cross-section for the scattering of a longitudinal meson becomes, for $\varepsilon < Mc^2$, assuming $\Delta M \ll \mu$,

$$\varphi = 4\pi \left(\frac{g^2}{\mu c^2} \right)^2 \left\{ \frac{1}{3} \left(\frac{\mu}{M} \right)^2 \left(\frac{\mu c^2}{\varepsilon} \right)^4 + \left(\frac{\Delta M}{\mu} \right)^2 \frac{p^4}{\varepsilon^4} \right\} \quad (2)$$

This expression does *not* increase with energy for $\varepsilon > \mu c^2$. If p is approximately μc^2 , (2) is smaller by a factor $(\Delta M/\mu)^2$ than (1). A value $\Delta M/\mu$ of approximately 1/5 would be sufficient to bring (2) into harmony with the experimental requirements. For ε greater than Mc^2 , φ will probably decrease owing to the relativistic features of the proton. 中文

Similar considerations must be applied to the spin. The spin contributes also to the high scattering cross-section (for transverse mesons). This can be avoided if we introduce also “higher spin states”, for example, heavy particles with spin s of 3/2. Transitions from the normal proton state, s equal to 1/2, to these higher states under the influence of a meson field can be included in the theory in a very simple manner. In the present theory the spin-dependent interaction between a meson field φ and a nuclear particle is $f/\lambda (\sigma \text{ curl } \varphi)$, where σ is the spin matrix and has only matrix elements for $\Delta s = 0$. σ has to be extended in such a way as to include transitions $\Delta s = 1$. This can be done if we replace σ by the matrix of a dipole moment $\mathbf{r}/r$. For transitions $\Delta s = 0$, the matrix elements of $\mathbf{r}/r$ and of σ are identical. If this is done, the cross-section for the scattering of transverse mesons also is small and of the order of magnitude (2). The physical significance of $\mathbf{r}/r$ is that of the *intrinsic* magnetic dipole moment of the proton, which is a characteristic feature of the meson theory ($\mathbf{r}$ is not, of course, the spacial position of the proton). 中文

As a further result of our new assumptions, the anomalous magnetic moments diverge only *logarithmically*. Such a divergence can, at the present stage of the theory of the meson, scarcely be considered as a very serious difficulty. The relativistic features of the proton have so

far been neglected, and it may well be that the logarithmic divergence would disappear if they are taken into account properly. As an upper limit for the validity of the meson theory in the form proposed above, we therefore take the rest energy of the proton. The anomalous magnetic moment of the proton then becomes (in units of the nuclear magneton μ_0)

$$\frac{\mu}{\mu_0} = \frac{16}{3\pi} \frac{M\Delta M}{\mu^2} \frac{f^2}{\hbar c} \left(\log \frac{2E_m}{\mu c^2} - \frac{4}{3} \right), \quad E_m \sim Mc^2 \quad (3)$$

This is of the right order of magnitude when $\Delta M/\mu$ is approximately 1/5, which is the value assumed above. 中文

(145, 29-30; 1940)

W. Heitler: H. H. Wills Physical Laboratory, University, Bristol, 8, Nov. 28.

References:

1. Fröhlich, Heitler and Kemmer, *Proc. Roy. Soc., A*, **166**, 154 (1938). Yukawa, Sakata and Taketani, *Proc. Math. Phys. Soc. Japan*, **20**, 319 (1938).
2. Heitler, *Proc. Roy. Soc., A*, **166**, 529 (1938), and Report of the Eighth Solvay Conference, Brussels, in the press, where the reasons for the high cross-section are analysed.
3. Wilson, *Proc. Roy. Soc.*, in the press. I am very much indebted to Dr. Wilson for having sent me his MS. before publication.
4. This possibility was first mentioned to me by Bhabha in a private discussion in connexion with his classical theory for neutral mesons. The whole problem was very much clarified in discussions with Bhabha, Fröhlich and Kemmer.

介子散射与质子和中子的磁矩

海特勒

瓦尔特·海因里希·海特勒是一位德国科学家，他于20世纪30年代移居英国。名为介子的物质粒子实际上并没有观察到，它们的存在只是推测；其作用被认为是核物质的粒子（比如中子和质子）之间作用力的媒介。这篇专业性很强的短文指出核内粒子的其他一些性质，如磁矩，也能被视为核力的介质，我们可以通过它们的功能函数计算得到它们的值。 [英文](#)

现有形式的介子理论呈现若干困难，这是与电荷守恒和自旋引入介子与核粒子之间相互作用的特殊方式相联系的。例如，质子和中子的反常磁矩表达式^[1]作为 $\int_0^{\infty} dk$ 是发散的。我们发现介子被核散射的截面比实验允许值大很多，而且其随着能量的增加而迅速增加。这种现象与宇宙线介子具有高穿透本领是相矛盾的。根据现有的理论，能量为 ε （动量为 p/c ）的纵向介子（静止质量为 μ ）的散射截面为^[2]

$$\sigma = 4\pi \left(\frac{g^2}{\mu c^2} \right)^2 \frac{p^4}{\varepsilon^2 (\mu c^2)^2} \quad (1)$$

[英文](#)

通过将介子与光子类比，我们可以预计散射截面的量级为 $(g^2/Mc^2)^2$ ，其中 M 为质子的质量，并且当能量 $\varepsilon > \mu c^2$ 时不再增加。由威尔逊^[3]的实验表明，即使在能量低至几倍 μc^2 （ 10^8 电子伏）时散射截面的量级比表达式（1）的值小，而且其值不随能量的增加而增加。 [英文](#)

从对表达式（1）的计算我们可以看出，前面所述的两种困难都源于电荷守恒禁止了一些跃迁这个事实，而如果介子是中性粒子这些跃迁

就会发生^[2]。例如，一个中性介子可以被一个质子发射和吸收。而一个正介子只能被一个质子发射却不能被其吸收。如果我们允许一个正介子也可以被一个质子吸收且一个负介子可以被一个质子发射等等，或者换句话说讲，如果带有 $-e$ 和 $+2e$ 电荷的“质子态”存在^[4]，那么将得出数量级正确的散射截面。但是这些粒子的引入会遇到下面的困难。首先，具有这些性质的粒子并没有被观测到，而如果它们在重核中出现时它们是不太可能不被观测到的。其次，如果一个质子也能够发射一个负介子，那么负介子会对异号质子的反常磁矩有一定的贡献，并且其他所有的量都是相同的话，这些贡献与来自正介子的贡献有相同的值，因此，根本就不会存在反常磁矩。 [英文](#)

如果假定这些新粒子的静止质量远远大于质子的质量，比如说为电子质量的25~50倍（见下文），我们就能够克服这些困难。那么，这些粒子将会极其不稳定，并且在重核结构中不会起任何作用。用 ΔM 表示新粒子与质子之间的质量差，当能量满足 $\varepsilon < Mc^2$ 时，假定 $\Delta M \ll \mu$ ，纵向介子的散射截面可以表示为：

$$\varphi = 4\pi \left(\frac{g^2}{\mu c^2} \right)^2 \left\{ \frac{1}{3} \left(\frac{\mu}{M} \right)^2 \left(\frac{\mu c^2}{\varepsilon} \right)^4 + \left(\frac{\Delta M}{\mu} \right)^2 \frac{p^4}{\varepsilon^4} \right\} \quad (2)$$

然而当能量满足 $\varepsilon > \mu c^2$ 时，这个表达式的值不会随能量增加。如果 p 趋近于 μc^2 ，表达式（2）比表达式（1）小 $(\Delta M/\mu)^2$ 倍。一个趋于1/5的 $\Delta M/\mu$ 值，足以使表达式（2）与实验要求相吻合。如果能量 ε 大于 Mc^2 ， φ 可能会因为质子的相对论特征而减小。 [英文](#)

对于自旋问题必须采取相似的分析思路。自旋同样会对高散射截面（对于横向介子）有贡献。如果我们同样引入“较高自旋态”，比如，具有自旋 $s=3/2$ 的重粒子，就可以避开这个问题。在介子场的影响下，自旋 $s=1/2$ 的正常质子态跃迁到较高能态，可以以非常简单的方式包含于理论中。在现有的理论中，介子场 φ 与核粒子之间与自旋相关的相互作用为 f/λ （ σ 与 φ 做旋度计算），其中 σ 为自旋矩阵，且仅当 $\Delta s = 0$ 时才有矩阵元。必须对 σ 矩阵进行扩展，这样才能够包含 $\Delta s = 1$ 的跃迁。如果我们用偶极矩 $\vec{r}/r$ 矩阵来替代 σ ，那么就可以满足上面的要求。对于 $\Delta s = 0$ 的跃迁， $\vec{r}/r$ 的矩阵元和 σ 的相同。假若这些得以实现，在 $\vec{r}/r$ 替代 σ 后，横向介子的散射截面仍然很小，同表达式（2）中的散射截面

具有一样的数量级。 $\vec{r}/r$ 的物理意义为质子的内禀磁偶极矩，这是介子理论的显著特点（当然， $\vec{r}$ 并不是质子的空间位置）。[英文](#)

作为新的假定所得到的进一步的结果是，反常磁矩仅仅是对数上的发散。从现阶段的介子理论看来，这种发散几乎可以不被当作一个很严重的困难。到目前为止，质子的相对论效应都被忽略了，如果对此进行适当的考虑的话，目前存在的对数发散也会消失。作为上述形式的介子理论有效性的上限，我们采用了质子的静止能量。因此质子的反常磁矩表示为（以核子的磁矩 μ_0 为单位）：

$$\frac{\mu}{\mu_0} = \frac{16}{3\pi} \frac{M\Delta M}{\mu^2} \frac{f^2}{\hbar c} \left(\log \frac{2E_m}{\mu c^2} - \frac{4}{3} \right), \quad E_m \sim Mc^2 \tag{3}$$

当 $\Delta M/\mu$ 趋于1/5时这是正确的数量级，而1/5正是上面所假定的值。

[英文](#)

（胡雪兰 翻译；张焕乔 审稿）

Evidence for Transformation of Mesotrons into Electrons

E. J. Williams and G. E. Roberts

If seeing is believing, then Figure 2*b* of this paper is a complete demonstration that mesons, thought to mediate nuclear forces between particles such as neutrons and protons, themselves decay into electrons. The tracks exhibited in this paper were made in a cloud chamber, a device filled with nearly super-saturated water vapour and air which can be expanded quickly, thus forming droplets of water wherever there are free electric charges in the chamber. The first author of this paper, Evan J. Williams, was one of the most talented British physicists of his generation. He died at the age of 43. (Since 1940, several different kinds of mesons have been discovered; that described in this paper is now called a π -meson.) 中文

ONE of the outstanding questions regarding the mesotron is that of its ultimate fate. Certain properties of this particle are remarkably like those of the hypothetical particle assumed by Yukawa in his theory of nuclear forces and β -disintegration, and this has led to the view that the two may be identical. Within a rather large experimental error they have the same mass, and both are unstable in the free state, having an average life of the order of 10^{-6} seconds. The disappearance of the particle of Yukawa's theory at the end of its life takes place through its transformation into an electron and a neutrino,

and it is regarding this that hitherto there has been no evidence of a parallel between it and the mesotron of cosmic rays. In fact, existing experimental evidence has rather gone to show that mesotrons suffer at the end of their life some other fate than befalls the Yukawa particle. 中文

With the object of obtaining information on this crucial point we constructed a large cloud-chamber (24 in. diameter, 20 in. deep) which, with its large sensitive period and volume, might catch a cosmic ray mesotron coming to the end of its range in the gas of the chamber. A recent photograph taken with this shows a mesotron track terminating in the gas as desired. From its end there emerges a fast electron track, the kinetic energy of which is very much greater than the kinetic energy of the mesotron, but is comparable with its mass energy. This indicates that the mesotron transforms into an electron, in which case the remarkable parallel between the mesotron and the Yukawa particle is taken one stage further. In terms of Yukawa's theory, the phenomenon observed may be described as a disintegration of the mesotron with the emission of an electron, thus constituting the most elementary form of β -disintegration. 中文

Fig. 1 is a reproduction of one of the photographs of the stereoscopic pair. The dense track *AF* is that of the mesotron, and the faint track *FG* leaving its end, near the bottom of the chamber, is that of the fast electron. It will be noticed that the latter is comparable in density with the tracks of other fast particles which happened to traverse the chamber in the same region. Fig. 2 is a larger reproduction of the stereoscopic pair, showing only the end portion of the mesotron track and the emergent electron (2*a* is not in as good focus as 2*b*). Fig. 3 is a heavily exposed reproduction of the last few millimetres of the mesotron track to bring out its shape though the electron track is thereby nearly lost, and Fig. 4 is an enlargement of the δ -track at *E* to show more clearly its initial direction. The tracks in the present

reproductions are much less distinct than in the original negatives and photographic prints, and this particularly applies to the fast tracks (including *FG*) and the short δ -tracks, of which there are at least six obvious ones to be seen between *C* and *F* on the original negative.

中文

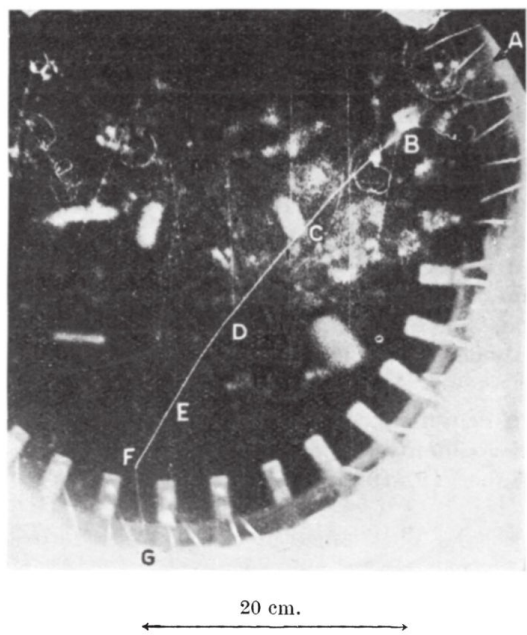


Fig. 1 中文

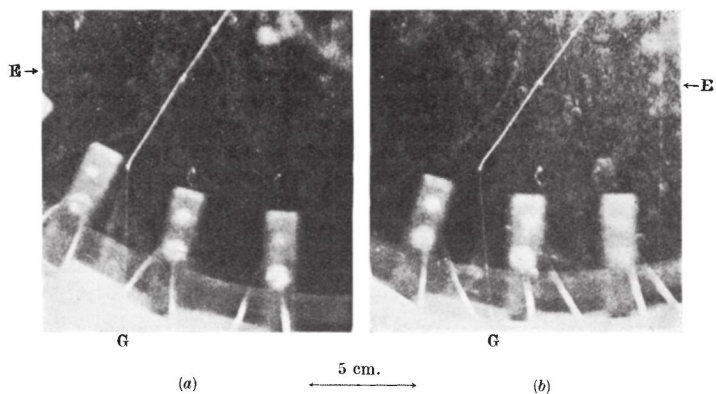
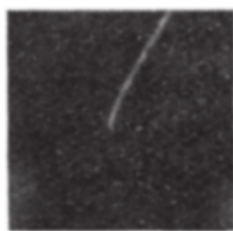


Fig. 2. *a* and *b* are arranged for stereoscopic observation with the naked eye, when usually the left eye sees the right-hand picture. 中文

That the dense track is that of a mesotron follows from its range and curvature, and from the δ -tracks. An accurate estimate of the mass

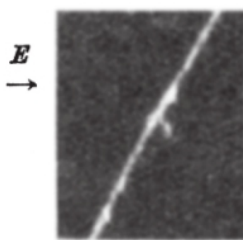
from the curvature is not possible because the scattering which the particle suffers interferes appreciably with the curvature due to the magnetic field. The straightness of FG and of neighbouring fast tracks shows that there was no appreciable distortion from air motion. The radius of curvature, ρ , at B , measured over AC (~ 20 cm.), is 70 cm., giving $H\rho = 1,180 \times 70 = 8.3 \times 10^4$. The range beyond B is 33 cm. in the chamber, corresponding to 41 cm. of normal air. These data give a mass, μ , of $(250 \pm 70) m$, where m represents electronic mass. This is of the same order as previous estimates of the mass of the mesotron, and is sufficiently far removed from the mass of the proton ($1,840 m$) to establish the particle as a mesotron. The number and range of the δ -tracks also indicate mesotronic mass, and rule out a proton. In particular the long δ -track at E , which in the reproduction in Fig. 3 is seen to be directed nearly forward, has a path-range, R' , equal to 0.06 ± 0.03 times the remaining range, R , of the heavy particle. This is roughly the range that would be expected for a secondary electron knocked nearly forward by a mesotron with the observed remaining range. It is, however, at least five times greater than the range of the longest δ -track that could be produced by a proton. The latter is approximately $(2^{3.4}/1,840) R = 0.006 R$. Regarding the "scattering" of the track, while it is more pronounced than the *average* effect expected for a mesotron, it is more compatible with the latter than with a proton or any other known particle. The natural "curvature" of cloud-tracks due to multiple and single scattering is discussed by one of us in a paper now in the press (*Physical Review*). It is there shown that towards the end of its range—last 5 cm. or so—the natural curvature of a mesotron track may well exceed its magnetic curvature in a field of 1,200 gauss. (The "kink" at D contributes little to the average curvature and is possibly more a thinning of the track on one side than a true deflection. The "single" scattering at C appreciably reduces the overall curvature.) The bending of the track in the last 5 mm. or so (Fig. 3) is of interest. It indicates that the mesotron has come to the end of its range, thus

discounting the possibility that the photograph represents the production of a mesotron and an electron by a neutral particle. Against this supposition are also the facts that the long δ -track at E is initially directed forward, and that the δ -tracks are more numerous in the lower half of the track. Both indicate motion of the mesotron towards F . 中文



2 cm.

Fig. 3 中文



1 cm.

Fig. 4 中文

The curvature of the electron track, FG , is very small. Actually there is detectable (Fig. 2b), a small curvature in a direction indicating a positive charge, which is also the direction of the curvature of the mesotron. The photograph thus represents a positive mesotron transforming into a positive electron. So far as it can be estimated, the radius of curvature of FG is $200 \text{ cm.} \pm 50 \text{ percent}$, which in the field of 1,180 gauss (neglecting any distortion due to air-motion) indicates an energy of $70 \text{ Mev.} \pm 50 \text{ percent}$. Taking $\mu = 200 m$, and assuming that a neutrino takes half the energy, the energy of the electron would be $100 mc^2 = 50 \text{ Mev.}$ 中文

The large energy of the electron shows, quite apart from Yukawa's theory, that mass has been annihilated—for the mesotron, even if we suppose it has disintegrated before “stopping”, has certainly less than 4 Mev. of kinetic energy. Actually, the large bending of the end of the mesotron track indicates (as already pointed out) that E is the normal end of its range, where it has reached too low a velocity to ionize further. In this connexion it is of interest that an upper limit to the lifetime, τ , of this mesotron, since its entry into the chamber, can be set from the fact that the electron track starts from a point certainly not more than 0.4 mm. from the end of the mesotron track. Assuming the mesotron, after it ceases to ionize, to diffuse with gas-kinetic free path (10^{-5} cm.) and thermal velocity (10^6 cm./sec.) this gives an upper limit to τ of $(0.042/10^{-5} \times 10^6) \sim 2 \times 10^{-4}$ seconds. Actually it is likely that a mesotron, when it stops ionizing, has a velocity of at least 10^7 cm./sec., and a free path considerably greater than gas-kinetic values, so that τ must be much less than the above limit. The average value of τ deduced from the anomalous absorption of cosmic ray mesotrons is of the order of 10^{-6} seconds. [中文](#)

(145, 102-103; 1940)

E. J. Williams and G. E. Roberts: University College of Wales, Aberystwyth, Dec. 21.

介子向电子转化的证明

威廉姆斯，罗伯茨

如果说眼见为实，那么本文图2b就是作为诸如中子和质子这样的粒子之间核力媒介的介子衰变成电子的实证。本文所展现的径迹是在云室中获得的，那是一个充满近乎过饱和水蒸气和空气并且其中的气体可迅速扩张的装置，这样在云室中只要是存在自由电荷的地方就会形成很多小水滴。本文的第一作者埃文·威廉姆斯是同时代人中最有才华的英国物理学家之一，享年43岁。（自1940年以来，已经发现了几种不同类型的介子，本文中描述的介子现在被称为 π 介子。） [英文](#)

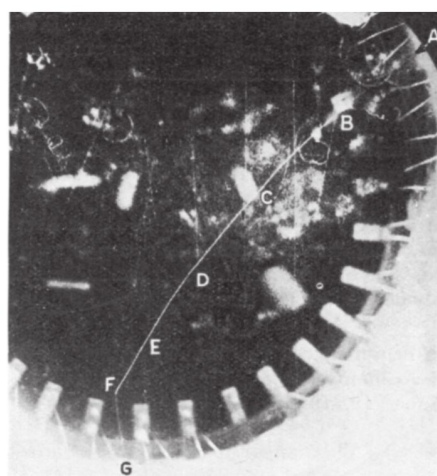
关于介子的一个最突出的问题是它的最终命运。这种粒子的某些性质与汤川秀树在他的核力和 β 衰变理论中假设的粒子的性质是明显一致的，这使得人们认为这两种粒子是同一种粒子。在相当大的实验误差范围内，它们具有相同的质量，而且在自由态时都是不稳定的，平均寿命的数量级为 10^{-6} 秒。汤川秀树理论中的粒子在其寿命结束时转化成电子和中微子，但至今都没有发现在这一点上它与宇宙线中的介子有相似之处的证据。事实上，有实验证据表明这种粒子在其寿命终结时会遭受另一种命运——一种不同于汤川秀树粒子的命运。 [英文](#)

为了得到与这个至关重要的问题有关的信息，我们构建了一个大云室（直径为24英寸，深度为20英寸），由于其具有高灵敏周期和庞大的体积，因此可以在云室气体中捕捉到即将到达其行程尽头的宇宙线介子。最近拍摄的相关照片中显示出了那些我们所期望得到的在气体中终结的介子径迹。其终结处出现快电子的径迹，快电子的动能明显大于介子的动能，但是质量和能量则与介子的相当。这表明，介子会转化成为电子。在这种情况下介子与汤川秀树粒子之间的相同之处又更近了一

步。根据汤川秀树的理论，观察到的这种现象可以这样描述，介子在衰变中发射了一个电子，从而构成了 β 衰变的一种最基本的形式。 英文

文

图1为其中一张立体像对照片的复制片。密集的径迹 AF 是介子的，而从其终端远去的那条模糊的、靠近云室底部的径迹 FG 则是快电子的。我们将会注意到，后者与碰巧在同一区域穿过云室的其他快速粒子的径迹在密度上是相当的。图2是立体像对照片的一个更大的复制片，仅仅显示了介子径迹的末端部分和出射的电子（ $2a$ 不如 $2b$ 的聚焦效果好）。图3为介子径迹最后几毫米的一个严重曝光的复制片，以此来显示介子的径迹形状，尽管这样基本上会看不到电子的径迹。图4是对 E 处 δ 径迹的放大，是为了更清楚地显示出其初始方向。在这里给出的复制片中的径迹不如原底片和用底片冲洗出来的照片中那么清晰，尤其是对于快电子的径迹（包括 FG ）和短的 δ 径迹，在原始底片中的 C 和 F 之间至少能够看到6条它们这样的清晰径迹。 英文



20 cm

图1 英文

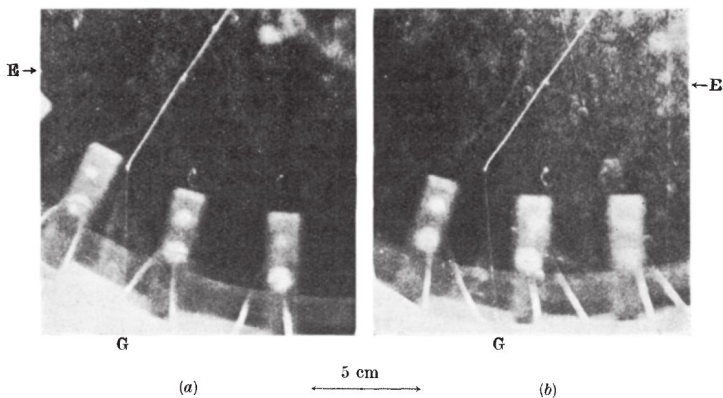


图2. *a*和*b*是为用肉眼进行立体观察所准备的，通常用左眼看着右手边的图片 英文

密集的径迹是介子的，这是根据该径迹的范围和曲率，以及 δ 径迹分析得出的。根据曲率是不可能精确估算出粒子质量的，因为粒子受到的散射对由磁场引起的曲率有明显的干扰。*FG*和近邻的快电子径迹的平直度表明，不存在明显的由空气运动而导致的畸变。在*AC*段（约20厘米）上测量到的*B*处的曲率半径 ρ 为70厘米，它使得 $H\rho = 1,180 \times 70 = 8.3 \times 10^4$ 。在云室中*B*以后的行程范围为33厘米，对应于普通空气中的41厘米。这些数据可以给出质量 μ 为 $(250 \pm 70)m$ ，其中 m 为电子的质量。这同先前估算的介子质量具有相同的量级，而且与质子质量 $(1,840m)$ 相差甚远，进而可以确定这一粒子为介子。 δ 径迹的数量和范围同样也表明了介子的质量，从而排除了质子的可能。特别是图3的复制片中*E*处的长 δ 径迹看上去几乎一直向前，这个直的径迹的行程长度*R'*，为普通重粒子的残留径迹*R*的 0.06 ± 0.03 倍。这就是介子在观测到的持续范围内被近似向前敲出的次级电子的粗略范围。然而，这至少比质子可以产生的最长 δ 径迹范围大五倍，后者大约是 $(2^{3.4}/1,840)R = 0.006R$ 。至于径迹的“散开”，虽然它比对介子预期的平均效应要更为明显，但是与质子或其他任何已知粒子相比，它同介子的更为符合。由多重和单个散射引起的云迹的自身“曲率”已被我们中的一位在一篇即将出版的文章中进行了讨论（《物理学评论》）。该文章指出，对于介子行程末端，大约是最后5厘米，其径迹自身的曲率会超过它在1,200高斯的磁场中的磁曲率。（*D*处的“纽结”对平均曲率几乎没有作用，与真正的偏转相比更有可能的情况是径迹一边的稀疏。*C*处的“单”散射明显使整个曲率减小了。）径迹的最后大约5毫米处的弯曲（图3）是非常有价值的。它表明了介子已经到达了其行程的末端，这就使照片表示由一

个中性粒子产生一个介子和一个电子的可能性不可置信。 E 处的长 δ 径迹最初是一直向前的事实，以及在径迹下半段 δ 径迹的数量更多的事实，也驳斥了这一假说。这两者均表明介子是朝向 F 方向运动的。 英文

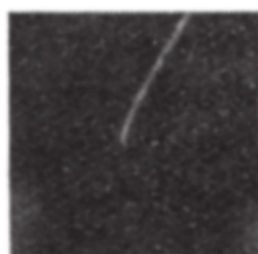


图3 英文

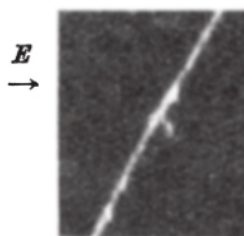


图4 英文

电子径迹 FG 的曲率是很小的。实际上可以发现（图2b）在一个表明是正电荷的方向上有一个较小的曲率，这个方向也就是介子曲率的方向。因此，照片所表示的是一个正介子正在向一个正电子转化的过程。到目前为止可以估算得出， FG 的曲率半径为 $200\text{厘米} \pm 50\%$ ，这表明在 $1,180$ 高斯的磁场中（忽略所有由空气运动造成的扭曲）能量为 70 兆电子伏 $\pm 50\%$ 。设 $\mu = 200\text{ m}$ ，并且假定一个中微子具有一半的能量，那么电子的能量将会是 $100\text{ mc}^2 = 50$ 兆电子伏。 英文

完全抛开汤川秀树理论，高的电子能量表明，质量已经湮没了。对于介子，即使我们假定它在“停止”之前已经衰变，它所具有的动能也小于 4 兆电子伏。实际上，介子径迹末端的大弯曲表明（正如以前所指出的） E 是它的行程范围的常规终点，到达此处时它所具有的速度太小，以致不能发生进一步的电离。关于这个问题值得注意的是，可以根据电

子径迹从介子径迹末端不超过0.4毫米处算起这一事实判断出介子进入云室后的寿命上限 τ 。假定介子不再电离后，沿着气体分子运动自由程（ 10^{-5} 厘米）以热速度（每秒 10^6 厘米）扩散，这就给定了寿命的上限 τ 为（ $0.042/10^{-5} \times 10^6$ ） $\sim 2 \times 10^{-4}$ 秒。事实上，很有可能的是介子在停止电离后，其速度至少为每秒 10^7 厘米，而其自由程比气体分子运动的价值要大很多，因此寿命上限 τ 肯定会远小于上述的值。由宇宙射线介子的反常吸收推断出 τ 平均值的量级为 10^{-6} 秒。 [英文](#)

（胡雪兰 翻译；厉光烈 审稿）

Capture Cross-sections for Thermal Neutrons in Thorium, Lead and Uranium 238

L. Meitner

Physicists had not yet measured the “capture cross-section”—the tendency to become captured—of thermal neutrons in the nuclei of ^{238}U , an important parameter for the possibility of a nuclear chain reaction. A small capture cross-section—fewer neutrons captured—would make the process more likely, as this leaves others to trigger fission events. Here Lise Meitner measures this cross-section in thorium and then uses it to estimate the corresponding value for uranium. Using a relationship derived by Niels Bohr linking the ratio of beta decay events in thorium and uranium, she reports a value very close to that reported independently by Enrico Fermi and Carl Anderson. [中文](#)

EXPERIMENTS on the processes arising in thorium under neutron bombardment have shown that nuclear fission is induced only by fast neutrons of energies of about 2 Mev. or more. There exists also a radiative capture process producing an isotope of thorium (Th 233) of 26 min. half-life; this process has a resonance character with a large contribution from thermal neutrons¹. So far, the capture cross-section of thermal neutrons in thorium has not been measured. The following experiments were carried out in order to determine this cross-section.

As the neutron source available was not very strong (100 mgm. Ra + Be), all dimensions had to be kept as small as possible. On the other hand, in order to obtain high accuracy of measurement, one had to use an absorbing thorium layer of reasonable thickness. By the kindness of Prof. Coster, I obtained a sample of metallic thorium of more than 99 percent purity. Dysprosium of the highest purity, also kindly given me by Prof. Coster, was used as detector. The thorium was almost exactly prismatic in form (1.2 cm. $\times$ 1.2 cm. $\times$ 2.96 cm.). The dysprosium was a thin layer (15.7 mgm./cm.² Dy) of rectangular form, 1.0 cm. $\times$ 2.7 cm., and its upper face was covered with 2 μ "Cellophane". For the absorption measurement the thorium was placed directly on the dysprosium with or without a cadmium screen, so that the neutrons impinging normally had to go through 1.2 cm. thickness corresponding to 13.4 gm. thorium. 中文

The experimental arrangement was as follows. In a plate of paraffin wax of 3.8 cm. thickness, there was cut out a rectangular cavity of 1.3 cm. depth, the bottom and sides of which were covered with cadmium of 0.5 mm. thickness so that thermal neutrons could not enter except from above. This plate was put between two other plates of paraffin wax, forming in this way a block of 11.5 cm. height and about 25 cm. $\times$ 25 cm. area. The dysprosium was placed on the cadmium-shielded bottom of the cavity. The upper paraffin plate contained the neutron source 3.3 cm. below the surface in such a way that the source just touched the upper edges of the cadmium screened cavity. 中文

The activity of the dysprosium detector was measured with a Geiger-Müller counter with 0.1 mm. aluminium walls connected to an amplifier. The dysprosium, the half-life of which was carefully determined and found to be 156 ± 3 min., was in all experiments irradiated up to saturation, and the decay of the activity was followed for several hours in order to increase the accuracy of measurements.

All measurements were referred to a uranium standard. The contribution from thermal neutrons was determined by carrying out the irradiation with and without 0.5 mm. cadmium directly over the exposed face of the detector. With cadmium screens on all faces of the detector, the observed activity is due to neutrons faster than thermal neutrons. Under the experimental conditions used here, it amounted to 9 percent of the activity obtained without cadmium on the exposed face. [中文](#)

For the determination of the capture cross-section for thermal neutrons in thorium, one has to consider the different kinds of interaction of neutrons with the thorium nucleus. The fission cross-section of fast neutrons is so small as to be negligible. The same holds for the radiative capture cross-section of fast neutrons. Therefore for fast neutrons one has to take into account the scattering cross-section only. Because of the arrangement used—the absorber being put directly on a detector of nearly equal size—one would expect that practically all the scattered neutrons would be efficient in the irradiation, that is, the scattering cross-section would not enter into these measurements. Experiment confirmed this expectation. When the detector was screened on both faces by cadmium, the measurements of the activity with and without thorium (or with and without lead) gave the same values within the experimental error of 2–3 percent. Further, in order to test the influence of inelastic scattering, the cadmium was placed by turns either directly on the exposed face of the detector (with the thorium put upon that), or between the neutron source and the thorium absorber. No difference could be detected. Thus the inelastic scattering does not give rise to thermal neutrons in any observable quantity, a result to be expected.

[中文](#)

These results suggest that, under the conditions actually used, the scattering of thermal neutrons too will be negligible, and thus the

decrease in activity (of about 28 percent) caused by the thorium absorber is due to radiative capture processes only. To obtain a direct proof the absorption in metallic lead was measured. The lead absorber had practically the same dimensions as the thorium absorber, but the thickness of the cast lead prism of density 10.6 was kept a little smaller (1.10 cm.) in order to have the same number of absorbing nuclei per cm.². 中文

Of course, in determining the cross-sections, the angular distribution of the thermal neutrons was taken into account and obliquity corrections (angles up to nearly 70° were involved) were made according to the data given by Frisch². 中文

The total cross-section for thermal neutrons in lead was found to be $\sigma_{\text{Pb}}^{\text{th}} = 2.5 \pm 0.2 \times 10^{-24}$ cm.². This value is in very good agreement with the value of 2.3×10^{-24} cm.² obtained by Fleischmann³ from γ -ray measurements. Thus one can be sure that for thorium too the radiative capture cross-section alone enters into the measurements. The value obtained is $\sigma_{\text{Pb}}^{\text{th}} = 6.0 \pm 0.3 \times 10^{-24}$ cm.². This cross-section can be used to evaluate the capture cross-section of ²³⁸U. In this isotope, as Bohr⁴ has emphasized, thermal neutrons do not produce fission processes. Thus when equal small quantities of uranium and thorium are subjected to neutron bombardment under identical conditions, ²³⁹U and ²³³Th respectively being produced, it is clear that if on account of their nearly equal half-life the efficiency of the β -rays is assumed to be approximately the same, the β -ray activities due to thermal neutrons (corrected for equal numbers of nuclei) must be proportional to the respective cross-sections:

$$\frac{T_{\text{U}(239)}^{\text{th}}}{T_{\text{Th}(233)}^{\text{th}}} = \frac{\sigma_{\text{U}(238)}^{\text{th}} \cdot \frac{1}{238}}{\sigma_{\text{Th}}^{\text{th}} \cdot \frac{1}{232}}$$

From earlier measurements carried out in Dahlem, I find for this ratio the value 1/4.15. Using the above value for the cross-section of thorium, the cross-section for uranium 238 is

$$\sigma_{\text{U}^{(238)}}^{th} = 1.5 \pm 0.2 \times 10^{-24} \text{ cm}^2.$$

中文

Anderson and Fermi⁵, measuring directly the β -ray intensity of ^{239}U due to a known number of thermal neutrons, found

$$\sigma_{\text{U}^{(238)}}^{th} = 1.2 \times 10^{-24} \text{ cm}^2.$$

Considering the possibility of fairly large errors in this type of measurement, the agreement is very good. 中文

I wish to express my gratitude to the Academy of Sciences for a grant and in particular to Prof. Siegbahn for the facilities kindly put at my disposal. 中文

(145, 422-423; 1940)

Lise Meitner: Forskningsinstitutet för Fysik, Stockholm, Feb.1.

References:

1. Meitner, L., Hahn, O., and Strassmann, F., *Z. Phys.*, **109**, 538 (1938).
2. Frisch, O. R., *Kgl. Dansk Vid. Selskab. Math. Phys. Medd.*, **14**, No. 5 (1936).
3. Fleischmann, R., and Bothe, W., *Ergeb. exact. Naturwiss.*, **16**, 37 (1937).
4. Bohr, N., *Phys. Rev.*, **55**, 418 (1939).
5. Anderson, H. L., and Fermi, E., *Phys. Rev.*, **55**, 1106 (1939).

钍、铅和铀-238中热中子的俘获截面

迈特纳

物理学家还没有测量出铀-238对热中子的“俘获截面”，该截面表征热中子被俘获的倾向，它是核链式反应可能性的一个重要参数。小的俘获截面表明有很少中子被俘获，这使得更有可能发生剩下的中子引发裂变的事件。本文中莉泽·迈特纳测量了钍的热中子俘获截面，然后用它估算铀中的相应值。根据尼尔斯·玻尔导出的钍核和铀核 β 衰变事例比值之间的关系，她宣称这个值与恩里科·费米和卡尔·安德森所报道的值非常接近。

[英文](#)

在用中子轰击钍的实验过程中，我们发现，只有能量大于或等于大约2兆电子伏的快中子才能诱发核裂变。这里也存在一个辐射俘获过程，产生了一个半衰期为26分钟的钍的同位素钍-233；而且这一过程具有源自热中子^[1]贡献的共振特征。迄今为止，热中子在钍元素中的俘获截面还没能被成功测量。为了测量出这个截面，我们做了下面的实验。

[英文](#)

由于可利用的中子源并不是特别的强（100毫克的镭和铍），所以全部实验材料的尺寸都要保持尽量的小。另一方面，为了得到高精度的测量结果，我们必须使用厚度合适的吸收钍片。在科斯特教授的慷慨帮助下，我得到了一个纯度高于99%的金属钍的样品。科斯特教授还提供了纯度最高的镅，我们把它用作探测器。钍样品的形状是一个规则的棱柱形（1.2厘米×1.2厘米×2.96厘米）。镅为一个矩形（1.0厘米×2.7厘米）的薄层（15.7毫克每平方厘米镅），上表面覆盖了一层2微米的“玻璃纸”。为了进行吸收测量，我们把钍直接放在带镅屏或者不带镅屏的镅片上，这样中子轰击时一般就必须通过厚度为1.2厘米的钍片，其

相当于13.4克的钷。 [英文](#)

具体的实验做法如下。在一个3.8厘米厚的石蜡平板上，挖出一个1.3厘米深的矩形空腔，底部和侧面都覆盖有0.5毫米厚的镅，这样使得热中子只能从上面进入。把这个石蜡板放在另外两个石蜡板的中间，用这种方法组成一个高11.5厘米、底面为25厘米×25厘米的长方体。镅放在被镅屏蔽了的空腔的底部。最上面的石蜡平板里含有一个中子源，中子源距离上表面3.3厘米，这样放置后，中子源就刚好接触到了被镅屏蔽的空腔的上边界。 [英文](#)

镅探测器的放射性是由盖革-米勒计数器进行测量的，计数器的壁是厚度为0.1毫米的铝箔，并与一个放大器相连。镅的半衰期被精确地测定为 156 ± 3 分钟，在所有的实验中，镅都会被强烈照射达到饱和，为了提高测量的精度，对镅放射性强度的衰减要跟踪数个小时。所有的测量都参照着铀的标准进行。对于探测器的被照表面直接覆盖和不覆盖0.5毫米镅这两种情形分别进行辐照测量，可以测定热中子的贡献。在探测器的所有面都有镅层屏蔽的时候，探测到的放射性来源于比热中子快的中子。在这里所使用的实验条件下，其放射性仅为无镅片屏蔽探测器被照表面情形下的9%。 [英文](#)

为了测定钷的热中子俘获截面，我们必须考虑到中子与钷核之间各种各样的相互作用。快中子的裂变截面很小几乎可以忽略。快中子的辐射俘获截面同样如此。因此，对于快中子来说，我们只需要考虑它的散射截面。由于实验安排中吸收体直接放在尺寸几乎相等的探测器的上面，可以认为实际上所有的散射中子在辐照中均是有效的，也就是说，这个散射截面在测量中不起作用。实验证实了这一推测。当探测器的两个面全被镅遮盖时，在实验误差2%~3%允许的范围内，实验中测得的有钷和没有钷时（或者有铅和没有铅）的放射性是一样的。为了进一步测定非弹性散射的影响，我们把镅先后放在探测器的被照表面（钷放在该表面之上）和中子源与钷吸收器的中间，分别对它进行了研究。结果显示没有任何的差别，因此，正如人们预测的那样，非弹性散射并不产生可观测到的热中子。 [英文](#)

这些研究结果表明，在实际使用的条件下，热中子的散射也是可以

忽略的，因此由钷吸收体导致的放射性的减少（28%左右）仅仅是由辐射俘获过程引起的。为了得到更直接的证明，我们对在金属铅中的吸收进行了测量。铅吸收体的大小实际上和钷吸收体相同，但是为了使单位面积上吸收体原子核的数量相同，密度为10.6的棱柱形铅铸件的厚度要小一些（1.10厘米）。 [英文](#)

当然，在测量截面的过程中，热中子的角分布也被考虑在内，而且根据弗里施^[2]提供的数据进行了倾斜度校正（最大角度接近70°）。

[英文](#)

经计算，铅的热中子总截面为 $\sigma_{\text{Pb}}^{\text{th}} = (2.5 \pm 0.2) \times 10^{-24}$ 平方厘米。这与弗莱施曼^[3]在 γ 射线测量中得到的结果 2.3×10^{-24} 平方厘米是非常吻合的。因此我们可以肯定，对于钷来说，在测量中也仅仅是辐射俘获截面起了作用。所测得的结果为 $\sigma_{\text{Th}}^{\text{th}} = (6.0 \pm 0.3) \times 10^{-24}$ 平方厘米，这个值可以用来估算铀-238的俘获截面。在这种同位素中，正如玻尔^[4]强调的，热中子不会诱发裂变。因此，当同样少量的铀和钷在相同的条件下受到中子的轰击时，结果就会相应地产生铀-239和钷-233。显然，考虑到它们的半衰期几乎都是相同的，如果假设产生 β 射线的效率也近似相等，那么由热中子（修正为相同数量的原子核）引起的 β 射线的放射性一定正比于相应的截面：

$$\frac{T_{\text{U}(239)}^{\text{th}}}{T_{\text{Th}(233)}^{\text{th}}} = \frac{\sigma_{\text{U}(238)}^{\text{th}} \cdot \frac{1}{238}}{\sigma_{\text{Th}}^{\text{th}} \cdot \frac{1}{232}}$$

[英文](#)

在达勒姆早期的测量中，我找到了这个比值为1/4.15。应用上面钷俘获截面的值，得出铀-238的俘获截面应为：

$$\sigma_{\text{U}(238)}^{\text{th}} = (1.5 \pm 0.2) \times 10^{-24} \text{ 平方厘米}$$

[英文](#)

安德森和费米^[5]通过直接测量由已知数量的热中子引起的铀-239的 β 射线强度，得出：

$$\sigma_{\text{U}^{238}}^{th} = 1.2 \times 10^{-24} \text{ 平方厘米}$$

考虑到这种类型的测量存在较大的误差，我们认为结果的一致性还是很好的。 英文

在此对科学院的资金支持表示衷心的感谢，尤其要感谢西格巴恩教授，他慷慨地为我提供了实验设备。 英文

（胡雪兰 翻译；朱永生 审稿）

The Mass Centre in Relativity

M. Born and K. Fuchs

Part of the interest of this paper is its authorship. Max Born was a German émigré to Britain, awarded a Nobel Prize in 1954 for his work on quantum mechanics, while Klaus Fuchs was also a German exile working as a physicist in Britain. Fuchs afterwards joined the Manhattan Project at Los Alamos, New Mexico, and was later convicted by the British government of espionage on behalf of the Soviet Union; he working in Berlin after serving a prison sentence. The point of their paper was to show that, despite appearances, relativity can deal well with the centre of mass of a collection of particles. [中文](#)

THE question whether there exists in relativity mechanics a theorem analogous to the classical law for the motion of the mass centre (conservation of total momentum) has, as far as we can see, never found a satisfactory answer. Eddington¹ has taken this fact as the starting point for a general attack against the usual application of wave mechanics to fast-moving particles without contributing himself anything positive to the question. The reason why this problem has never been seriously treated seems to be this. [中文](#)

In classical mechanics the internal potential energy depends on the simultaneous relative positions of the particles; therefore one can separate the relative motion from the translatory motion of the centre. In relativity, however, all forces are retarded, the interaction does not

depend on simultaneous relative positions and the separation of the relative motion from the translation of the whole system loses its meaning. [中文](#)

Quantum mechanics circumvents this problem by considering interactions as produced by emission and reabsorption of other particles. We were induced to reconsider this problem by its bearing on a relativistic and “reciprocal” formulation of second quantization. Without touching this question, we shall state here some simple results concerning free particles. It is clear that in this case there must exist a “rest system” Σ^0 , that is, a Lorentz frame in which the total momentum vanishes. The problem is to describe the relative motion in an invariant way. [中文](#)

We start by bringing the classical derivation into a form permitting generalization. If $\mathbf{r}_1, \mathbf{r}_2$ are the position vectors, $\mathbf{p}_1, \mathbf{p}_2$ the momenta of two particles, we form the vector of relative position and that of total momentum

$$\boldsymbol{\rho} = \mathbf{r}_1 - \mathbf{r}_2, \mathbf{P} = \mathbf{p}_1 + \mathbf{p}_2 \quad (1)$$

and determine their canonical conjugate variables' components of the vectors $\boldsymbol{\pi}$ and $\mathbf{R}$. A simple calculation shows that these are not uniquely determined but have the form

$$\boldsymbol{\pi} = (1 - a) \mathbf{p}_1 - a \mathbf{p}_2, \mathbf{R} = a \mathbf{r}_1 + (1 - a) \mathbf{r}_2, \quad (2)$$

where a is an arbitrary constant. Hence another condition must be added. [中文](#)

We postulate that the kinetic energy $p_1^2/2m_1 + p_2^2/2m_2$ assumes the form $P^2/2m + \pi^2/2\mu$. This condition leads to a determination of the

three constants a, m, μ , namely,

$$a = \frac{m_1}{m_1 + m_2}, \quad m = m_1 + m_2, \quad \mu = \frac{m_1 m_2}{m_1 + m_2},$$

which introduced into (2) give the usual expressions for relative momentum and centre of mass. [中文](#)

In relativity, the energies E_1, E_2 of two free particles are given by

$$E_1^2 = m_1^2 + p_1^2, \quad E_2^2 = m_2^2 + p_2^2. \quad (3)$$

[中文](#)

We consider now the 4-vectors $\mathbf{p}_+ = \mathbf{p}_1 + \mathbf{p}_2, E_+ = E_1 + E_2$ and $\mathbf{p}_- = \mathbf{p}_1 - \mathbf{p}_2, E_- = E_1 - E_2$. A simple calculation leads to

$$E_+^2 = m_+^2 + p_+^2 + \pi^2, \quad E_-^2 = m_-^2 + p_-^2 - \pi^2; \quad (4)$$

here $m_+ = m_1 + m_2, m_- = m_1 - m_2$

and

$$\pi = 2m_1 m_2 \sinh \Gamma / 2, \quad (5)$$

where Γ is the “angular distance” of the two 4-vectors, given by

$$m_1 m_2 \cosh \Gamma = E_1 E_2 - \mathbf{p}_1 \mathbf{p}_2. \quad (6)$$

Γ is invariant, hence π is invariant also. π has a simple meaning in the case of equal masses. In the rest system Σ° , where $\overset{\circ}{P} = \overset{\circ}{p}_+ = \overset{\circ}{p}_1 + \overset{\circ}{p}_2 = 0$, we have $m_1 - m_2 = m_- = 0$, and $\overset{\circ}{E}_1 - \overset{\circ}{E}_2 = \overset{\circ}{E}_- = 0$; hence $\pi^2 = (\overset{\circ}{p}_-)^2$. This shows that π is the length of the vector π representing relative momentum. [中文](#)

For different masses π can be described as the relative momentum in that Lorentz frame (which always exists) in which

$$E_1 - E_2 = \pm (m_1 - m_2).$$

中文

The first equation (4) can now be written

$$E^2 = M^2 + P^2, M^2 = \mu^2 + \pi^2, \quad (7)$$

Where $\mu = m_1 + m_2$ is the sum of the rest masses, M the total internal energy, which represents also the rest mass of the whole system, and $\mathbf{P} = \mathbf{p}_+ = \mathbf{p}_1 + \mathbf{p}_2$ the total momentum. 中文

Taking the components of $\mathbf{P}$ and π as new canonical momenta, one can determine the conjugate coordinates, $\mathbf{R}$ and ρ . They are linear in $\mathbf{r}_1, \mathbf{r}_2$; the coefficients are, however, not constants but functions of $\mathbf{p}_1, \mathbf{p}_2$. 中文

For small $\mathbf{p}_1, \mathbf{p}_2$ the formulae reduce to the classical ones. 中文

It is interesting to remark that in relativity there exists a “reciprocal”² theorem obtained by interchanging coordinates and momenta. 中文

(145, 587; 1940)

Max Born and Klaus Fuchs: Department of Applied Mathematics, University of Edinburgh.

References:

1. Eddington, A., *Proc. Camb. Phil. Soc.*, **35**, 186 (1939).
2. Born, M., *Proc. Roy. Soc. Edinburgh*, (ii), **59**, 219(1939).

相对论中的质心

玻恩，富克斯

本文作者是这篇文章令人感兴趣的原因之一。马克斯·玻恩是流亡到英国的德国人，1954年因为他在量子力学方面的工作获得了诺贝尔奖，而克劳斯·富克斯也是从德国流亡至英国并在英国工作的物理学家。后来富克斯加入了在美国新墨西哥州洛斯阿拉莫斯实施的“曼哈顿计划”，之后被英国政府以苏联间谍的名义定罪；刑满之后他回到柏林工作。他们这篇文章的观点认为，相对论并不像表现的那样，实际上它可以很好地处理一个粒子集合的质心问题。 [英文](#)

在相对论力学中是否存在一个类似于经典质心运动定律（总动量守恒）的定理，关于这个问题，就我们所知尚未找到一个满意的答案。爱丁顿^[1]以这个事实作为出发点，对通常将波动力学应用到快速运动粒子的做法进行了一般性的抨击，而他自己却没有对此问题做出任何积极的贡献。这似乎就是此问题从未被认真对待的原因。 [英文](#)

在经典力学中，内部势能取决于粒子的瞬时相对位置；因此，我们可以将相对运动从质心的平移运动中分离出来。然而在相对论中，所有的力都是迟滞的，相互作用并不取决于瞬时相对位置，所以把相对运动从整个系统的平移运动中分离出来是没有意义的。 [英文](#)

量子力学把相互作用当作是由其他粒子的发射和重吸收所引起的，以此来规避这个问题。这使得我们需要通过一个相对论的和“倒易的”二次量子化公式来重新考虑这个问题。暂不考虑这个问题，我们在此将给出一些关于自由粒子的简单结果。显然，在这种情况下，必然存在一个“静止系统” Σ^0 ，即一个总动量等于零的洛伦兹参考系。具体来说，这个问题就是要以一种不变量的形式对相对运动进行描述。 [英文](#)

我们先把经典推导变为允许进行推广的形式。如果 $\vec{r}_1$ 、 $\vec{r}_2$ 是两个粒子的位置矢量， $\vec{p}_1$ 、 $\vec{p}_2$ 是它们的动量，我们可以得出相对位置的矢量和总动量的矢量为：

$$\vec{\rho} = \vec{r}_1 - \vec{r}_2, \quad \vec{P} = \vec{p}_1 + \vec{p}_2 \quad (1)$$

我们还可以确定其正则共轭变量，即矢量 $\vec{\pi}$ 和 $\vec{R}$ 。经简单的计算表明，它们并不是唯一确定的，而是具有下列形式：

$$\vec{\pi} = (1 - a) \vec{p}_1 - a \vec{p}_2, \quad \vec{R} = a \vec{r}_1 + (1 - a) \vec{r}_2 \quad (2)$$

式中 a 是一个任意常数。因此，必须加入另一个条件。 [英文](#)

我们假定，动能 $p_1^2/2m_1 + p_2^2/2m_2$ 满足 $P^2/2m + \pi^2/2\mu$ 的形式。根据这个条件可以确定三个常数 a 、 m 和 μ ，即

$$a = \frac{m_1}{m_1 + m_2}, \quad m = m_1 + m_2, \quad \mu = \frac{m_1 m_2}{m_1 + m_2},$$

将它们代入式（2）可得相对动量和质心的通常表达式。 [英文](#)

在相对论中，两个自由粒子的能量 E_1 、 E_2 如下式：

$$E_1^2 = m_1^2 + p_1^2, \quad E_2^2 = m_2^2 + p_2^2 \quad (3)$$

[英文](#)

我们现在考虑4矢量 $\vec{p}_+ = \vec{p}_1 + \vec{p}_2$ ， $E_+ = E_1 + E_2$ 以及 $\vec{p}_- = \vec{p}_1 - \vec{p}_2$ ， $E_- = E_1 - E_2$ 。简单的计算可导出：

$$E_+^2 = m_+^2 + p_+^2 + \pi^2, \quad E_-^2 = m_-^2 + p_-^2 - \pi^2 \quad (4)$$

式中， $m_+ = m_1 + m_2$ ， $m_- = m_1 - m_2$

且

$$\pi = 2m_1 m_2 \sinh \Gamma/2$$

(5)

其中 Γ 是这两个4矢量的“角距离”，如下式：

$$m_1 m_2 \cosh \Gamma = E_1 E_2 - \vec{p}_1 \vec{p}_2 \quad (6)$$

Γ 是不变量，因此 π 也是不变量。在两个自由粒子的质量相等的情况下， π 的含义是简单的。在静止系 Σ° 中， $\vec{P} = \vec{p}_+ = \vec{p}_1 + \vec{p}_2 = 0$ ，我们已知 $m_1 - m_2 = m_- = 0$ ，及 $\vec{E}_1 - \vec{E}_2 = \vec{E}_- = 0$ ；因此 $\pi^2 = (\vec{p}_-)^2$ 。这表明 π 是表示相对动量的矢量 $\vec{\pi}$ 的长度。 [英文](#)

对于两个自由粒子的质量不相同的情况，在使下式成立的洛伦兹系（它总是存在的）中， $\vec{\pi}$ 是相对动量。

$$E_1 - E_2 = \pm (m_1 - m_2)$$

[英文](#)

（4）中的第一个方程现可写为：

$$E^2 = M^2 + P^2, M^2 = \mu^2 + \pi^2, \quad (7)$$

式中， $\mu = m_1 + m_2$ 是静止质量之和， M 是总内能，它也代表整个系统的静止质量， $\vec{P} = \vec{p}_+ = \vec{p}_1 + \vec{p}_2$ 是总动量。 [英文](#)

取 $\vec{P}$ 和 $\vec{\pi}$ 的分量为新的正则动量，我们可以确定共轭坐标 $\vec{R}$ 和 $\vec{\rho}$ 。它们对于 $\vec{r}_1$ ， $\vec{r}_2$ 是线性的；然而系数不是常数，而是 $\vec{p}_1$ 、 $\vec{p}_2$ 的函数。 [英文](#)

当 $\vec{p}_1$ 、 $\vec{p}_2$ 很小时，该公式可简化为经典形式。 [英文](#)

值得注意的是，在相对论中存在着“倒易”^[2]定理，它是通过交换坐标和动量得到的。 [英文](#)

（沈乃澍 翻译；张元仲 审稿）

The Theory of Nuclear Forces*

R. Peierls

Rudolph Peierls offers a summary of the emerging theory of nuclear forces. These forces could be most easily probed in two-particle interactions involving neutrons and protons. Scattering experiments had established the range of the force as about 1.2×10^{-13} cm, and supported the notion that the nuclear forces between neutrons and protons were identical, ignoring electrostatic differences. Nuclear forces could also depend strongly on direction in relation to the orientation of quantum-mechanical spins of the particles. The best theory proposed so far was that of Japanese physicist Hideki Yukawa, which viewed the nuclear force as originating from a nuclear field associated with a new quantum particle having mass of around 300 electron masses—later identified with the pion. [中文](#)

THE forces between the constituents of a nucleus are “short-range” forces, which have no appreciable effect over distances of more than a few times 10^{-13} cm. Hence it is impossible to find the laws of force by extrapolation from large-scale observations (as in the case of Coulomb’s law) and the only possible lines of attack are either, to deduce the law of force from direct observations on the properties of nuclei, or to derive them from some simpler, and more general, laws.

[中文](#)

Using the direct experimental approach, it is best to start from

phenomena which involve only two particles, since only these permit an unambiguous theoretical interpretation. This group consists of the properties of the deuteron, including its disintegration, and the scattering of protons and neutrons by hydrogen. [中文](#)

Practically all experiments are carried out in conditions in which the de Broglie wave-length of the particles is greater than the range of the forces, and this has the effect that one need consider only those states of motion in which the motion of one particle with respect to the other has no angular momentum. (In all other states of motion the centrifugal force prevents the particles from approaching sufficiently close for any interaction to take place.) Moreover, so long as the wave-length is greater than the range of the force, the effect of the field of force is largely independent of the exact variation of force with distance within the range, and depends approximately only on one constant, which may be called the “strength” of the field of force. (In the case of a potential of the type of a potential well, this strength is approximately proportional to the depth times the square of the width.)¹ [中文](#)

In the experiments on proton-neutron interaction two possible cases are discussed, according to whether the spins of the two colliding particles are parallel or opposite (in the case of like particles, Pauli's principle ensures that, so long as there is no orbital angular momentum, the spins are necessarily opposite) and the strength of the interaction may be different for these two cases. For the case of a proton and a neutron with parallel spin; the strength constant can be obtained from the binding energy of the deuteron; for those with opposite spin, it follows from the scattering of neutrons by protons, since in this scattering the effect of the neutrons with parallel spin can be allowed for once their strength constant is known. The very high cross-section for slow neutrons is an indication that the strength constant of the interaction for neutrons with opposite spin is either

just sufficient or just insufficient to give rise to a bound state of the deuteron with no resultant spin². The choice between these alternatives can be made by means of the scattering of neutrons in *para*- and *ortho*-hydrogen where, because of interference, the results depend on the phase of the wave scattered by each proton. The result is that the force is just insufficient to give a bound state³. [中文](#)

For the proton-proton force, the strength can be derived from measurements of the scattering of protons in hydrogen. [中文](#)

Once these strength constants are known it is possible to calculate all other observable quantities, namely, the energy variation of the proton-proton and neutron-proton scattering, the photo-effect of the deuteron, etc., to the degree of approximation in which the ratio between the range of the forces and the de Broglie wave-length is negligible. The fact that these calculations give approximate agreement with observations serves as a check on the initial hypothesis of short-range forces. [中文](#)

Actually, all results of this simple theory have to be supplemented by correction terms involving the range. If the experimental data were accurate enough, it should thus be possible to estimate the range of the forces. The use of these correction terms requires greater accuracy than is at present available in the data on neutron-proton scattering, and the determination can only be carried out in the case of the proton-proton scattering, in which more accurate data have been obtained. The result of this is that the “range” for this interaction is about 1.2×10^{-13} cm. The experimental data are even accurate enough to yield a certain amount of information on the actual dependence of the force on distance⁴. [中文](#)

More information on these points would be obtained by measuring the neutron-proton scattering at medium energies with higher accuracy, or by observations at higher energies including, in particular, the

angular distribution of the scattered particles.

中文

An important contribution to the problem was the discovery by Rabi and others of a quadrupole moment of the deuteron⁵. This proves that the neutron and proton have a tendency to have their spins in the direction of the line joining them, rather than at right angles to it. This implies obviously that the forces are not central, but that the potential energy depends on the angle between the spin direction and the line joining the two particles. Although all the calculations referred to above were carried out on the assumptions of central forces, the results remain practically unchanged. For opposite spins, which is the only case of interest for proton-proton interaction at low energies, the force must still be central, since the resultant spin is zero and hence does not set up a preferential direction; for parallel spin, the fact that the force is not central means that the angular momentum due to the motion of the particles is no longer constant but fluctuates. Hence the motion in the state of lowest energy is no longer one with zero orbital angular momentum; it can be shown that the state of motion is a mixture of a state with zero angular momentum and one with two units (*S* and *D* states in spectroscopic notation). From the electrical quadrupole moment one can estimate that the contribution of the *D* state amounts to only a few percent⁶.

中文

However, an appreciable non-central force is required to produce even this small effect, since in the *D* state a very strong centrifugal force has to be overcome. It seems probable, therefore, that the non-central forces must represent an appreciable fraction of the total force. Yet, again owing to the effect of the centrifugal force, no appreciable influence of this *D* state should be expected on the other observable phenomena, except possibly on some finer features which have not yet been thoroughly investigated. Thus the approximate agreement with the experimental evidence, and the estimate of the range remain

practically unaffected by the correction terms. [中文](#)

The data on the strength and the estimate of the range give the same answer, within the experimental error, for the proton-proton and proton-neutron interactions for opposite spins, and the suggestion has therefore been made that these two forces are exactly the same, except for the electrostatic interaction between the protons (“charge-independence hypothesis”)⁷. [中文](#)

From the fact that the charge of stable light nuclei is about half their mass, and that only a small change is produced in the energy of a light nucleus if in its constituents the number of neutrons and the number of protons are interchanged, has further led to the belief that the nuclear forces are symmetric in proton and neutron, that is, the neutron-neutron interaction is exactly the same as the proton-proton interaction, except for the effect of the electric forces¹. [中文](#)

Turning now to the evidence from nuclei containing more than two particles, this is usually discussed on the basis of the assumption that the forces are additive; that is, that the interaction force between two particles is not affected by the simultaneous presence of a third particle. Beyond its simplicity and the fact that it holds in the atom, this assumption is not founded on any evidence, and, in fact, there are certain theoretical arguments against it⁸. However, without this assumption the available evidence is insufficient to draw any conclusions at all, and one must therefore use the assumption of additivity as a working hypothesis, which may at a later stage be disproved. Moreover, most of the theoretical work on the nuclei of weight 3 and 4 was done before the discovery of the quadripole moment of the deuteron, and hence central forces were used. It is likely that the directional dependence of the force will not be negligible in these problems, but its precise effect has yet to be investigated. [中文](#)

So far as the calculations go, they show that the mass defects of the nuclei of mass 3 and 4 are very sensitive to the range of the force, and that the range required to give the right values is roughly of the same order of magnitude as that obtained from scattering experiments^{1,9}. Quantitative agreement, however, was not obtained. The laws of force used in these calculations were usually restricted by adopting the charge-independence hypothesis, and also by assuming that the range of the force was the same for parallel and for opposite spins. Whether the remaining discrepancy is due to these restrictions, or to the assumption of central forces, or whether it represents a failure of the additivity, remains to be seen. [中文](#)

For nuclei beyond ${}^4\text{He}$, the observed binding energy ceases to rise rapidly with the number of particles. This fact, often briefly referred to as “saturation”, obviously means that the constituent particles of a large nucleus do not *all* attract each other with the same forces with which the constituents of a helium nucleus attract each other. This may be due to several reasons. For one thing, the additivity of the force might fail, and the attractive force between two particles may depend on the number of other particles in the immediate neighbourhood. This dependence might be such as to ensure that the total potential energy per particle always remained below a certain saturation value. A possible description on these lines has been put forward by Teller, Critchfield and Wigner¹⁰, but the idea has not yet been pursued very far. [中文](#)

Another possibility is that the attraction may turn into repulsion at very close approach, in analogy with the forces between the atoms of a liquefied inert gas. In this case the repulsion might ensure that any one particle can, within the range of its forces, be surrounded only by a small number of others, and hence the binding energy per particle is again limited. This possibility has not been fully explored, but it has the disadvantage that, owing to the wave mechanical penetrability of

potential barriers, an extremely strong repulsion would have to be assumed to make this explanation possible. [中文](#)

The most attractive explanation is no doubt that the forces are “exchange forces” which depend on the symmetry of the wave function describing the motion of the particles, like the valency forces between the constituents of organic molecules. On this idea the neutron is trivalent, capable of forming a “bond” with one other neutron and two protons, and correspondingly for the proton. This would give a very natural explanation of the helium nucleus as a saturated structure¹. [中文](#)

The directional properties of the forces, which must be inferred from the existence of the quadripole moment of the deuteron, may have a bearing on this question, since in a large nucleus different particles must necessarily be arranged in different directions relative to a given particle, and the forces may quite well be attractive for some pairs of particles and repulsive for others, if the directional dependence of the forces is strong⁶. This effect will give rise to some kind of saturation; whether this saturation is of the right kind, and in particular whether it leads naturally to the α -particle as a stable structure, remains to be seen. [中文](#)

Of the attempts to derive the nuclear forces from a more elementary phenomenon, the most interesting is the meson theory, which is based on an idea of Yukawa¹¹. Yukawa supposes that the nuclear forces are due to a “nuclear field” in the same manner in which the electromagnetic forces are caused by the electromagnetic field. This field must, however, satisfy different field equations in order to produce short-range forces, and if this requirement is coupled with that of the principle of relativity, there is only one possible type of wave equation, and the law of interaction is limited to laws of a particular type, of which the simplest has the potential:

$$V = g e^{-kr}/r,$$

(1)

where k and g are constants, and r is the distance between the particles. (Coulomb's law is a special case of this with $k = 0$). In quantum theory, just as the electromagnetic field is associated with light quanta, the "nuclear field" will be associated with a new type of particle; the fact that the wave equation differs from that of light indicates that the rest mass of these particles is not zero, like that of light quanta, but has the finite value $hk/2\pi c$, where k is the same constant as in (1). In order to obtain a range of the right order of magnitude this mass has to be assumed to be a few hundred times that of the electron. The subsequent discovery of "mesons" of just such a mass in cosmic rays has very much increased our confidence in the "meson theory" of nuclear forces. [中文](#)

If we try to fit a law of the form of (1) to the observations on proton-proton scattering, we obtain very good agreement, but we have to choose a value of k which corresponds to a meson mass of about 300 electron masses. This is almost certainly higher than the mass of the mesons found in cosmic rays. The origin of this discrepancy is not clear. [中文](#)

On the meson theory of nuclear forces, mesons are capable of being absorbed and emitted in nuclear reactions provided sufficient energy is available for their creation, and they may be exchanged (that is, temporarily created by one particle and absorbed by another) even if the available energy is insufficient to liberate them. If this view is taken, conservation of angular momentum in the process requires the mesons, like light quanta, to have integral spins. (The electron, which has a half-integral spin, can only be absorbed or produced in pairs.) Zero spin would make the nuclear forces repulsive when they should be attractive, and the most likely assumption seems that of a spin of

one unit, as for the photon¹².

中文

This assumption fixes the equations of the meson field completely, but not its interaction with the proton and neutron. This interaction is governed by two terms which, by analogy with the electric charge and magnetic moment, one may term the “meson charge” and the “meson moment” of the heavy particles. The law (1), in particular, is obtained if the heavy particles have only a meson charge g , but no meson moment. This law does not agree with experiment in detail, since it gives neither a spin dependence of the force (as required to explain the properties of the neutron-proton scattering) nor a directional dependence that would account for the quadripole moment of the deuteron. The introduction of a “meson moment” would help to give the right dependence¹², but the force would then increase so rapidly at short distances that the proton and the neutron would fall into another, producing an infinite binding energy. Probably this result should not be taken too seriously, since the methods of quantum theory are likely to fail for too close approach, but it would mean in any event that the quantitative study of nuclear forces would have to be abandoned until an exact description of this failure of quantum theory is available.

中文

It has also been suggested that two kinds of mesons might exist, of which one has the spin one, the other zero spin, and with such properties that the singular terms in the interaction energy just cancel. In the crude approximation to which such calculations are usually carried out, the directional dependence of the forces would then also just cancel, together with the infinities, but it is possible that finer effects would give a sufficiently large directional variation¹³.

中文

Lastly, there arises the question as to the electric charge of the meson. The mesons observed in cosmic rays are charged, and if one of them is emitted by one nuclear particle and absorbed by another, this will involve an exchange of charge, thus ensuring that the forces are of the

exchange type, as required by the most widely accepted explanation of the saturation of nuclear forces. Such an exchange will, however, be possible only if one of the heavy particles is a proton and the other a neutron, but not for two like particles. In order to account for the equally strong forces between like particles, one has to assume the existence of neutral mesons in addition to the charged ones¹⁴. There is certain independent evidence for the existence of neutral mesons in cosmic rays¹⁵. If we take the view that the saturation of the nuclear forces is due to their directional dependence and not to their exchange character, it is, in fact, possible to attribute *all* nuclear forces to neutral mesons⁶. This would have the advantage of removing the discrepancy between the mass of the charged mesons from cosmic rays, and the range of the forces as determined from proton-proton scattering. It would mean, on the other hand, that the particles, the discovery of which was hailed as a confirmation of Yukawa's theory, had actually no connexion with the particles postulated by Yukawa.

中文

This summary of the present state of the theory¹⁶ closes with a number of questions to which the answer is not known. But the fact that it is possible to ask these questions at all is a sign of the rapid progress that has been made in this field in the last few years. 中

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(145, 687-690; 1940)

Rudolph Peierls: University of Birmingham.

References:

1. Bethe and Bacher, *Rev. Mod. Phys.*, **8**, 82 (1936).
2. Simons, *Phys. Rev.*, **55**, 793 (1939).
3. Brickwedde, Dunning, Hoge and Manley, *Phys. Rev.*, **54**, 266 (1938).
4. Hoisington, Share and Breit, *Phys. Rev.*, **56**, 884 (1939).
5. Kellogg, Rabi, Ramsay and Zacharias, *Phys. Rev.*, **55**, 318 (1939).
6. Bethe, *Phys. Rev.*, **55**, 1261 (1939).
7. Breit, Condon and Present, *Phys. Rev.*, **50**, 825 (1936).

8. Primakoff and Holstein, *Phys. Rev.*, **55**, 1218 (1939).
9. Rarita and Present, *Phys. Rev.*, **51**, 788 (1937); Rarita and Slawsky, *Phys. Rev.*, **54**, 1053 (1938).
10. Wigner, Critchfield and Teller, *Phys. Rev.*, **56**, 530 (1939).
11. Yukawa, *Proc. Phys. Math. Soc. Japan*, **17**, 48 (1935).
12. Fröhlich, Heitler and Kemmer, *Proc. Roy. Soc., A*, **166**, 154 (1938).
13. Möller and Rosenfeld, *Nature*, **144**, 241 (1939); **144**, 476 (1939).
14. Kemmer, *Proc. Cam. Phil. Soc.*, **34**, 354 (1938).
15. Arley and Heitler, *Nature*, **142**, 158 (1938).
16. Cf. also Peierls, R., *Ann. Rep. Chem. Soc.*, in the press.

* Based on lectures given at the Royal Institution on January 17, 24 and 31.

核力的理论*

佩尔斯

鲁道夫·佩尔斯概述了现有的关于核力的理论。这种力可以很容易地在含有质子和中子的两粒子相互作用中被探测到。散射实验确定这种力的作用距离大约为 1.2×10^{-13} 厘米，同时在忽略静电力差别的前提下，实验也支持了作用于中子之间、质子之间和中子-质子之间的核力是相同的这一观点。核力在很大程度上还由方向决定，该方向与粒子的量子力学自旋取向有关。目前关于核力的最好理论是由日本物理学家汤川秀树提出的，这一理论认为核力源于一种新的质量约为300个电子质量的量子粒子所产生的核场，这一粒子后来被定义为 π 介子。 [英文](#)

核的各组分之间的力是“短程力”，当各组分之间的距离超过几个 10^{-13} 厘米时，这个力的作用效果就不明显了。因此，利用大尺度的观测结果（如库仑定律适用的情况）进行推导来得到力的定律是不可能的，因此仅有的两种处理方法是，要么对核的性质进行直接观测来推导微观尺度下力的定律，要么从一些更简单、更一般的定律去导出它们。

[英文](#)

利用直接的实验方法，最好从只包含两个粒子的现象出发，因为只有这类情况才有可能作出清晰的理论解释。这样的组合具有氦核的性质，包括氦核的蜕变，以及质子和中子在氦核上的散射。 [英文](#)

实际上，所有的相关实验都是在粒子的德布罗意波长大于力程的条件下进行的，在这种情况下，我们只需要考虑相对于另一个粒子而言角动量为0的粒子的运动状态。（在所有其他运动状态下，离心力使粒子间保持一定的距离从而不能产生相互作用。）此外，只要波长大于力程，在力程的距离范围内，力场的影响在很大程度上与力的精确变化无

关，而几乎仅仅取决于一个常数，我们称之为力场的“强度”。（对于具有势阱形式的势能来说，这种强度近似正比于势阱深度与势阱宽度平方的乘积。）^[1] [英文](#)

在质子-中子相互作用的实验中，对两个碰撞粒子的自旋呈平行和反平行这两种可能的情况分别进行了讨论（对于同类粒子，只要轨道角动量为0，泡利不相容原理将确保两个粒子的自旋方向必然是相反的），这两种情况中质子-中子相互作用的强度有可能不同。对于自旋方向相同的质子和中子，强度常数可以由氘核的结合能得到；而对于那些自旋方向相反的质子和中子，强度常数可以通过中子对质子的散射来确定，在这种散射中，一旦获知它们的强度常数，我们就可以考虑自旋平行的中子的效应了。慢中子的截面非常高，这表明与自旋相反的中子间相互作用的强度常数或者刚好能够又或者刚好不够形成总自旋为0的氘核束缚态^[2]。我们可以通过仲氢和正氢中的中子散射对以上两种可能的结果做出判断，由于中子散射中干涉现象的存在，这个结果取决于每一个质子的散射波的相位。结果是这个力刚好不足以形成束缚态^[3]。

[英文](#)

对于质子-质子之间的作用力，可以通过测量氢核上的质子散射来导出该作用力的强度。 [英文](#)

一旦知道这些强度常数，在力程与德布罗意波长之比可以忽略不计的近似程度下，我们就有可能计算得到所有其他的可观测量，即质子-质子散射和中子-质子散射的能量变化量、氘核的光效应等。这些计算结果与观测结果近似一致，这一点可用来检验与短程力有关的最初假设。 [英文](#)

实际上，所有这些简单理论的结果都必须加上与力程有关的修正项。只有实验数据足够准确，才有可能对力程进行估计。考虑这些修正项时所需数据的精确度要比目前在中子-质子散射中获得的数据的精确度更高，因此只有在质子-质子散射情况下，得到了更加精确的数据以后，我们才能确定力程的值。结果是，这种相互作用的“力程”约为 1.2×10^{-13} 厘米。在实验数据更加准确的情况下，我们将可得到一些关于力与距离的明确关系的信息^[4]。 [英文](#)

以更加精确的方式对中等能量的中子-质子散射进行测量，或者通过在更高能量情况下的观测，特别是对散射粒子的角分布的观测，我们都将获得更多关于这些问题的信息。 [英文](#)

拉比及其他研究人员发现的氘核的四极矩对此问题有重要的贡献^[5]。这证明了中子和质子的自旋方向倾向于与它们的连线方向一致，而不是与连线方向垂直。这显然意味着，中子与质子之间的力并不是中心力，而且它们之间的势能与自旋方向和两个粒子的连线方向之间的夹角有关。尽管上面提到的所有计算都是在中心力的假设前提下进行的，但实际上结果并没有因为该假设成立与否而发生变化。在低能量的质子-质子相互作用中，我们唯一感兴趣的是自旋相反的情况，其中的作用力一定仍是中心力，这是因为该情况下的合自旋为零，没有产生任何的偏向；对于自旋平行的情况，作用力不是中心力意味着由粒子运动产生的角动量不再是常数，而是有涨落的。因此，粒子在最低能态中的运动不再是轨道角动量为0的状态，研究发现此运动状态是一个包含角动量等于0和2两种情况（用光谱学符号表示为S态和D态）的混合态，根据电四极矩我们能估计出D态的贡献只占几个百分点^[6]。 [英文](#)

然而，即使D态产生的效应很小，我们仍需要一个可观的非中心力来产生这个效应，因为D态中需要克服一个很强的离心力。因此，非中心力在合力中占有相当大的比重是很有可能的。然而，也是由于离心力的作用，除了一些可能尚未彻底研究过的某些较细微的特性外，预计D态不会对其他可观测的现象产生明显的影响。因此，修正项并不会影响理论与实验现象的近似吻合以及力程的估计结果。 [英文](#)

在实验误差范围内，对于自旋相反的质子-质子相互作用和质子-中子相互作用，作用强度数据和力程的估算结果给出了同样的答案。由此可知，除了质子间的静电相互作用外，这两种相互作用力是完全相同的（“电荷独立性假说”）^[7]。 [英文](#)

稳定轻核的电荷数约为其质量数的一半，并且核组分中的中子数与质子数相互交换时，轻核的能量只会发生微小的变化，上述两个事实使我们更加相信质子和中子间的核力是对称的，也就是说，除了电场力的影响以外，中子-中子相互作用与质子-质子相互作用是完全相同的^[1]。

下面来讨论含有两个以上粒子的核的相关证据，这些研究通常是以力具有可加性这一假设为基础的，即两个粒子之间的相互作用力不受同时存在的第三个粒子的影响。除了假设的简单性及其在原子中成立的事实以外，这个假设的建立没有任何根据，实际上，甚至存在某些理论论据认为该假设是不成立的^[8]。然而，如果没有这个假设，现有证据是根本不足以得出任何结论的。因此，我们必须把可加性的假设作为有效的假说来使用，当然后面的研究有可能会证明该假设是不正确的。此外，在发现氦核的四极矩以前，人们就已经完成了大部分质量数为3和4的核的理论工作，因此当时的相关工作都采用了中心力的假设。实际上，这些问题中力对方向的依赖性很有可能是不可忽略的，但是它的确切的效应还有待研究。

英文

现在的计算结果表明质量数为3和4的核的质量亏损与力程密切相关，得出正确结果所需的力程与散射实验得到的力程在量级上大致相等^[1,9]。然而，在定量结果上并没有取得一致。上述计算中用到的作用力的相关定律通常受到以下两个条件的限定，即电荷独立性假说以及自旋平行和自旋反平行两种情况中力程相同的假设。至于定量结果的不一致是由这些限制引起的，还是由中心力的假设引起的，或者它是否代表了可加性的失效，这些还有待研究。

英文

对于质量数超过 ^4He 的核，观测到的结合能不再随着粒子数的增加而快速增长。我们通常把这种现象简单称之为“饱和”，这显然意味着，大核内粒子之间彼此吸引的力，并不都与氦核内粒子间相互吸引的力相同。这可能是由多种原因造成的。一方面，力的可加性可能失效，两个粒子之间的吸引力可能与邻近的其他粒子的数目有关。这种关系可能使每个粒子的总势能始终保持在一定的饱和值以下。特勒、克里奇菲尔德和维格纳^[10]已对此提出了一种可能的描述，但该想法还没有得到深入研究。

英文

另一种可能性是两个粒子在非常接近的情况下吸引力有可能转变为排斥力，这与液化惰性气体中原子之间的力相类似。在这种情况下，斥力可以确保任何一个粒子在其力程范围内，只被少量的几个粒子所包

围，因而每个粒子的结合能仍是有限的。这种可能性还没有得到充分的研究，但是根据势垒在波动力学下的穿透原理，这种可能性的缺点是，为了确保这种解释可能是正确的，必须假定斥力的强度非常大。 [英文](#)

而最具吸引力的解释无疑是，这些力是与描述粒子运动的波函数的对称性有关的“交换力”，类似于有机分子组分之间的化合价力。按照这种观点，中子是三价的，它能够与另外一个中子及两个质子形成一个“键”，相应地，质子也具有类似的性质。这将为具有饱和结构的氦核给出一个很自然的解释^[1]。 [英文](#)

必须从氦核中四极矩的存在推出粒子间作用力的方向性，这或许与以上论述的问题有关，因为在一个大原子核内，不同的粒子相对于某个给定粒子的排列方向必定都不一样，而如果这些粒子间作用力的方向依赖性很强的话^[6]，那么这些作用力很有可能对某些粒子对而言是吸引力，而对其他粒子对而言则是排斥力。这种效应将导致某种饱和；但这种饱和是否是上述的那种饱和现象，特别是，能否自然地解释 α 粒子是一种稳定的结构，这些还有待观察。 [英文](#)

在所有尝试从更加基本的现象出发来推导核力的理论中，最令人关注的是基于汤川秀树^[11]关于介子理论的一个构想。汤川秀树认为，核力是由“核场”引起的，这与电磁力是由电磁场引起的相类似。但是，为了产生短程力，这个场必须满足不同的场方程，而如果这个要求与相对性原理相结合，则只可能存在一种形式的波动方程，相互作用的定律也被限制在某种特定类型的定律之中，其中最简单的势能表达形式如下所示：

$$V = ge^{-kr}/r \quad (1)$$

式中 k 和 g 是常数， r 是粒子之间的距离。（库仑定律是上式中 $k=0$ 时的一种特殊情况。）在量子理论中，正如电磁场是与光量子相联系的，“核场”也将与一种新型的粒子相关联；其波动方程与光的波动方程不同，这一事实表明，与光量子不一样，这些粒子的静止质量不为0，而具有有

限值 $hk/2\pi c$ ，其中 k 是式（1）中的常数。为了得到合适的数量级范围，必须假设这个粒子的质量是电子质量的几百倍。随后在宇宙射线中发现的“介子”正好具有这样的质量，这大大增强了我们对核力的“介子理论”的信心。 [英文](#)

假如我们试图用一个具有式（1）形式的定律来拟合观测到的质子-质子散射，将会获得吻合得很好的结果，但为此我们必须选取一个 k 值，该值对应的介子质量约为电子质量的300倍。几乎可以肯定的是，这比在宇宙射线中发现的介子质量要高。而这种差异的根源尚不清楚。

[英文](#)

在核力的介子理论中，当系统提供形成介子所需的足够能量时，介子将能够在核反应中被吸收和发射，但即使系统提供的能量并不足以释放出介子时，介子仍可以发生交换现象（即在极短的时间内介子由一个粒子产生后马上被另一个粒子吸收）。如果采用这种观点，该过程中角动量守恒要求介子如光量子一样，具有整数自旋。（具有半整数自旋的电子只能成对地被吸收或发射。）假设自旋为0的话将使原本应该为引力的核力表现为斥力，因此最有可能的假设似乎应该是，介子如同光子一样，具有一个单位的自旋^[12]。 [英文](#)

这个假设使介子场方程完全确定下来了，但介子场与质子和中子的相互作用还不确定。这类相互作用是由类似于电荷和磁矩的两个因素决定的，我们称之为重粒子的“介子电荷”和“介子矩”。特别地，假设重粒子只具有介子电荷 g ，而不具有介子矩时可得到定律（1）。这个定律在细节上与实验结果并不一致，因为它既没有给出自旋与力的关系（在解释中子-质子散射的性质时需要用到），也没有给出可用来解释氦核四极矩的方向依赖关系式。引入“介子矩”将有助于给出正确的依赖关系^[12]，但在距离很近时，作用力将会迅速增大，使质子和中子落入到另一个核子之中，形成一个无限大的结合能。也许我们不该过于认真地看待这个结果，因为在粒子距离非常接近的情况下量子理论的方法可能是失效的，但这也可能意味着，在对量子理论失效的原因进行准确的说明以前，在任何情况下都不得不放弃对核力做定量研究的努力。 [英文](#)

也有人提出，可能存在两类介子，其中一类自旋为1，而另一类自

旋为0，在这种假设性质下，相互作用能中的奇异项恰好得以消除。在粗略的近似下，通常会进行这类计算，从而表示力的方向依赖性的项连同无限大的项一起，也刚好得以消除，但可能出现的情况却是，更加细微的效应将会使力在方向上出现足够大的变化^[13]。 [英文](#)

最后，出现了与介子电荷有关的问题。在宇宙射线中观测到的介子是带电的，而如果其中的一个介子是由一个核粒子发射并被另一个核粒子吸收，那么这就将涉及电荷的交换，因此，如同最为广泛接受的关于核力饱和的解释所要求的那样，这些力应该保证是交换型的力。然而，这样的交换仅可能在重粒子中的质子和中子之间发生，而不可能出现在两个相同类型的粒子之间。为了解释同类粒子间大小相同的力，就必须假定除带电介子外，还存在中性介子^[14]。而宇宙射线中存在着中性介子，这是有独立可靠的证据的^[15]。如果我们接受这样的观点，即认为核力的饱和是由核力对方向的依赖性所致而不是由其交换特性所致，那么实际上就可以认为所有的核力都是由中性介子引起的^[6]。这将会带来的好处是，消除了宇宙射线中带电介子的质量与质子-质子散射过程所确定的力程之间的不一致。另一方面，它也将意味着，这个被认为确证了汤川秀树理论的粒子的发现，实际上与汤川秀树假设的粒子无关。 [英文](#)

这篇有关核力理论现况^[16]的综述，以许多尚未解决的难题作为结尾。但是，能提出这些问题本身就标志着最近几年这一领域取得了迅速的进展。 [英文](#)

（沈乃澂 翻译；厉光烈 审稿）

* 基于1月17日、24日和31日在英国皇家研究院所做的演讲。

Excited States of Stable Nuclei

C. F. Powell *et al.*

The idea that the stable nuclei of many atoms could exist in excited energetic states was first canvassed by a group of scientists who had used the newly built cyclotron at the University of Liverpool to bombard atomic nuclei such as neon. This paper shows that neon does indeed have an excited state lying some 2.5 million electron volts above that of the ground state, but that oxygen appears not to have an excited state within the range explored. Of the authors, Cecil Frank Powell and James Chadwick won Nobel Prizes for their work. Alan Nunn May, a lecturer at King's College London, was compromised by his association with Klaus Fuchs, afterwards shown to be a Soviet spy. [中文](#)

WE have recently carried out some experiments on the scattering of protons by light elements, using the proton beam provided by the Liverpool cyclotron and detecting the scattered particles by the photographic method. [中文](#)

A proton beam of about 10^{-8} amperes, with a divergence of one degree, is defined by a system of stops, and emerges from an attachment to the vacuum tank of the cyclotron into the "camera"

through a mica window covering a hole $\frac{1}{8}$ in. in diameter. In the camera this narrow proton beam passes down the axis of a tube, which is interrupted for a length of 3 mm. to allow the scattered particles to emerge. A flat photographic plate is placed so that its

surface is parallel to the axis of the beam and at a distance of 1 cm. from it. The protons scattered by the gas with which the camera is filled emerge through the interruption and enter the plate at a small glancing angle. This arrangement has the advantage that a single plate can contain the information for determining the probability of scattering from about 15° to 150° , providing for each angle regions containing a suitable number of tracks for counting purposes. At the same time, the energy of the scattered particle can be determined from the length of its track in the photographic emulsion. [中文](#)

Once the difficulties of defining the beam in the stray field of the magnet had been overcome, we found that suitable exposures could be obtained for some six to eight different scattering gases per day.

[中文](#)

We have taken plates of the scattering from eleven elements which could be obtained either as elementary gases or in the form of suitable gaseous compounds. The energy of the incident particles at the point of scattering was about 4 million volts. The plates for hydrogen, deuterium and helium are satisfactory, and work is proceeding on these; but we wish to direct attention here to the inelastic scattering which accompanies the elastic scattering from the heavier elements, and gives information about the excited states of the stable nuclei in a particularly direct way. [中文](#)

The distributions in energy of the protons scattered through 90° from the gases oxygen and neon are shown in Fig. 1. In oxygen a single peak appears, corresponding in energy to protons elastically scattered through 90° . With neon, in addition to the elastically scattered group, there is a peak at lower energy which we attribute to inelastic scattering from ^{20}Ne . This view is supported by the fact, deduced from the analysis of the neutron spectrum of fluorine under deuteron bombardment, that ^{20}Ne has an excited state of 1.4 Mev., for the difference in energy of the two groups of scattered particles is just of

this amount.

中文

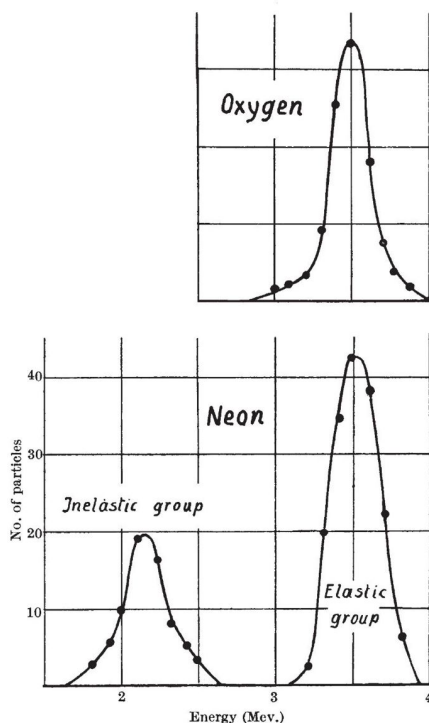


Fig. 1 中文

We have examined the variation of the probability of scattering with angle for elastic and inelastic scattering in neon, and the results are shown in Fig. 2. It will be seen that in the range from 40° to 80° the elastic scattering follows very closely that expected from pure Coulomb scattering. In contrast with this, the inelastically scattered particles are distributed spherically symmetrically about the centre of mass of the system, to within the present accuracy of the measurements. This suggests that the inelastically scattered protons have been “evaporated” from the compound nucleus formed in a close collision of an incident proton and a ^{20}Ne nucleus. 中文

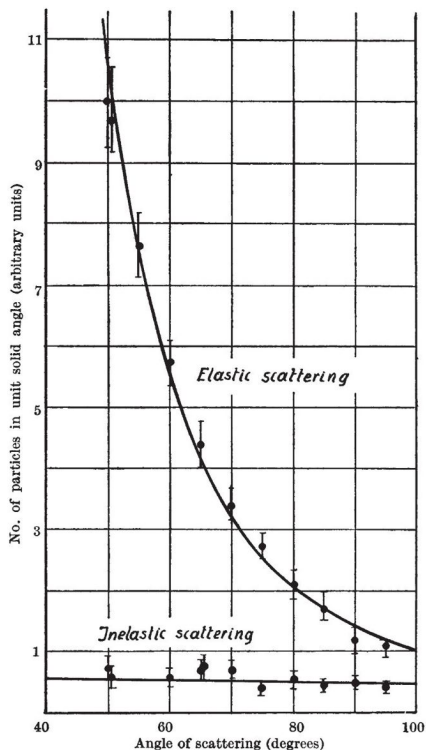


Fig. 2 中文

The absence of inelastically scattered protons in oxygen in the conditions of our experiments is evidently due to the fact that there is no excited state of oxygen below 4 Mev. The variation of scattering with angle shows, however, strong anomalies from Rutherford scattering at angles greater than about 45°, the number of scattered particles per unit solid angle varying only slowly with angle. This point will be investigated further. 中文

With the elements of atomic number greater than that of neon which we have examined, such as chlorine and argon, the ratio of the number of inelastically to elastically scattered particles is very much smaller than in the case of neon, corresponding to the decreasing probability of the protons entering the nucleus with increasing nuclear charge. It is therefore evident that it will be desirable to continue the experiments with protons of higher energy in order that the higher excited states of the light elements may become accessible to

investigation, and to obtain results for elements of higher atomic number. It is clear from our experience, however, that the method is very powerful, the plates being obtained with an exposure of a few minutes and the analysis of the energy distribution of the scattered protons being complete within a few hours. Also the use of what are essentially gas targets gives the advantage of purity control and absence of effects associated with energy loss in the target. We may expect these advantages in experiments of a similar character with high-energy deuterons, where the scattered primary particles may be accompanied by disintegration products. [中文](#)

In general, we may conclude that, using the photographic method of detection, it becomes possible to take advantage of the high-energy particles provided by the cyclotron to make experiments of the kind which have hitherto only been undertaken with direct current generators at relatively low energies. [中文](#)

(145, 893-894; 1940)

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A. N. May: King's College, London.

J. Chadwick and T. G. Pickavance: George Holt Physics Laboratory, University of Liverpool.

稳定核的激发态

鲍威尔等

一些科学家利用利物浦大学新建的回旋加速器轰击原子核（如氘），从而首次对激发能态下多种原子的稳定核能够存在的观点进行了探讨。这篇论文表明，氘确实存在一个激发态，且该激发态能量比基态能量大约高2.5兆电子伏，但是在实验研究范围内氧似乎没有激发态。本文作者中的塞西尔·弗兰克·鲍威尔和詹姆斯·查德威克凭借他们的研究成果获得了诺贝尔奖。另一位作者艾伦·农·梅是伦敦国王学院的一位讲师，他因与克劳斯·富克斯（后被发现是苏联间谍）有交往而受到了牵连。 [英文](#)

最近，我们利用一些轻元素进行了质子散射的实验，实验使用利物浦的回旋加速器来产生质子束，并用照相的方法来检测散射粒子。

[英文](#)

我们把一束强度为 10^{-8} 安培、分散度为 1° 的质子束，约束于一个静止的系统中，然后将其从回旋加速器的真空罐的附加装置中射出，穿过覆盖了云母窗的直径为 $1/8$ 英寸的小洞后进入“照相机”。在照相机中，这条狭窄的质子束沿着一个长管轴向穿行，这一长管有个3毫米长的断口，散射粒子能从这个断口中逃逸出来。在与质子束的轴向相平行的方向上放置一块扁平的照相底板，底板与质子束的轴相距1厘米。被充满于照相机中的气体所散射的质子能够穿过长管的断口，并以很小的掠射角射到底板上。这样安置的好处是，假如每个角度区域中都包括适当数量的能用于计数的轨迹的话，那么只用一块底板就能获得用以确定 15° 到 150° 范围内散射概率的相关信息。与此同时，我们还能通过照相乳胶中轨迹的长度来确定散射粒子的能量。 [英文](#)

如果能够克服在磁体的杂散场中约束质子束的困难，那么我们一天

就能得到大约6~8种不同气体散射质子的合适的曝光照片。 [英文](#)

我们已经得到了11种元素散射质子的底板，实验中采用的这些元素有的是单质气体的形式，有的是适当的气态化合物的形式。入射粒子在散射点的能量约为4兆电子伏。由氢、氖和氦得到的底板是令人满意的，后续处理的工作还在进行中；但是在这里，我们想把注意力放在较重元素中与弹性散射伴随出现的非弹性散射上，这种非弹性散射以特别直接的方式给出了关于稳定核激发态的信息。 [英文](#)

图1显示了在氧气和氖气中散射后偏转了90°的质子的能量分布。在氧气中散射的结果是，只有一个单峰，其对应着发生弹性散射后偏转了90°的质子的能量。而在氖气中散射的结果是，除了弹性散射组之外，在能量较低的位置上还有一个峰，我们将其解释为由²⁰Ne导致的非弹性散射。这一观点是有事实依据的，因为，对氟在氖核轰击下得到的中子能谱进行的分析表明²⁰Ne具有一个能量为1.4兆电子伏的激发态，而我们的实验结果中两组散射粒子的能量差刚好就是这个数值。 [英文](#)

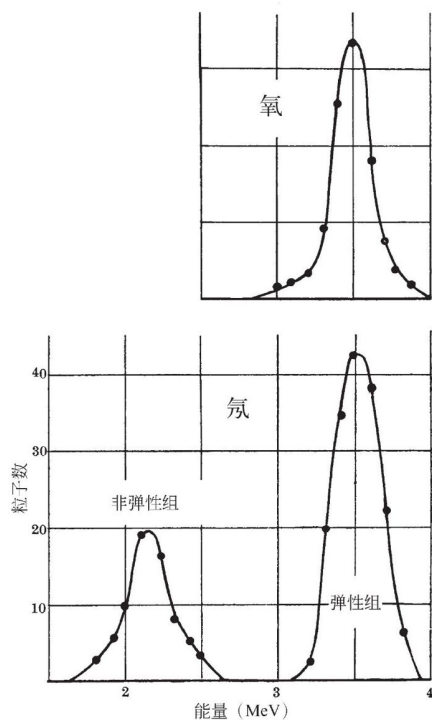


图1 [英文](#)

我们还研究了氖实验中弹性散射和非弹性散射的散射概率随角度的变化，结果如图2所示。从图中我们可以看到，在角度为 $40^{\circ}\sim 80^{\circ}$ 的范围内，弹性散射的结果与完全由库仑散射而得到的预期结果几乎完全吻合。但与此相反的是，在目前观测所能达到的精度范围内，非弹性散射粒子是以系统质心为中心呈球对称分布的。这意味着，一个入射质子与一个 ^{20}Ne 核发生近程碰撞后形成了复合核，其中非弹性散射质子就是从这个复合核中“蒸发”出来的。

英文

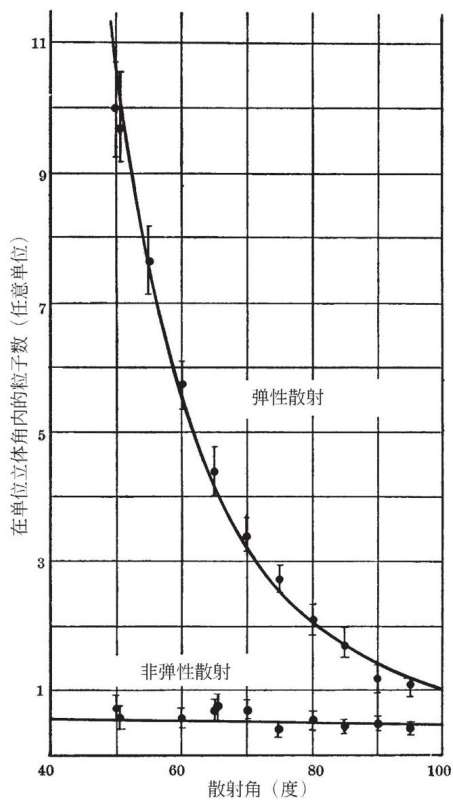


图2 英文

在我们的实验条件下，氧的实验中没有出现非弹性散射质子，这显然是因为氧不存在比基态能量高出4兆电子伏以内的激发态。不过，依据散射随角度的变化关系显示，在大于 45° 时散射结果严重背离了卢瑟福散射，且随着角度的变化，单位立体角中散射粒子的数目只发生缓慢的变化。在后面的工作中我们将对此进行深入的研究。

英文

对于我们研究过的原子序数比氖大的元素，比如氯和氩，非弹性散

射粒子数与弹性散射粒子数的比值远远小于氦实验中得到的结果，这与核电荷增大导致质子入核概率减小是相一致的。因此，要研究轻元素的更高能激发态，或者要得到较大原子序数元素的质子散射结果，就必须用更高能量的质子来进行实验。不过，从我们的实验中可以清楚地看出，我们用的这种方法是非常强大的，短短的几分钟就可以得到曝光底板，而对散射质子能量分布的分析结果也能在短短的几个小时之内完成。另外，至关重要的是，气体靶标的使用有利于纯度控制以及与靶标中的能量损失相关的各种效应的消除。我们可以预期，在使用高能氦核进行的类似实验中这些优点也将会得以体现，只是在这些实验中被散射的入射粒子可能会与衰变产物混在一起。 [英文](#)

总之，我们可以确定的是，如果使用照相法来进行检测，那么此前那些只能依靠直流发生器在相对较低的能量水平上进行的实验，现在就可以利用由回旋加速器产生的高能粒子来进行了。 [英文](#)

（王耀杨 翻译；汪长征 审稿）

Considerations Concerning the Fundamentals of Theoretical Physics*

A. Einstein

Five years before his death, Einstein had been driven to the view that quantum mechanics was a valid description of quantum phenomena but that as a consequence physics had been robbed of its explicit and deterministic foundations. He concluded that “it is open to every man to choose the direction of his striving; and also every man may draw comfort from Lessing’s fine saying that the search for truth is more precious than its possession”. 中文

WHAT we call physics comprises that group of natural sciences which base their concepts on measurements; and the concepts and propositions of which lend themselves to mathematical formulation. Its realm is accordingly defined as that part of the sum total of our knowledge which is capable of being expressed in mathematical terms. With the progress of science, the realm of physics has so expanded that it seems to be limited only by the limitations of the method itself. The larger part of physical research is devoted to the development of the various branches of physics, in each of which the object is the theoretical understanding of more or less restricted fields of experience, and in each of which the laws and concepts remain as closely as possible related to experience. It is this department of

science with its ever-growing specialization, which has revolutionized practical life in the last centuries. [中文](#)

On the other hand, from the very beginning there has always been present the attempt to find a unifying theoretical basis for all these single sciences, consisting of a minimum of concepts and fundamental relationships, from which all the concepts and relationships of the single disciplines might be derived by logical process. This is what we mean by the search for a foundation of the whole of physics. [中文](#)

It is clear that the word foundation in this connexion does not mean something analogous in all respects to the foundations of a building. Logically considered, of course, the various single laws of physics rest upon this foundation. But whereas a building may be seriously damaged by a heavy storm or spring flood, and yet its foundations remain intact, in science the logical foundation is always in greater peril from new experiences or new knowledge than are the branch disciplines with their closer experimental contacts. [中文](#)

The first attempt to lay a uniform theoretical foundation in physics was the work of Newton. In his system everything is reduced to the following concepts:

- (1) Mass points with invariable mass;
- (2) action at a distance between any pair of mass points;
- (3) law of motion for the mass point.

There was not, strictly speaking, any all-embracing foundation, because an explicit law was formulated only for the actions-at-a-distance of gravitation; while for other actions-at-a-distance nothing was established *a priori* except the law of equality of *actio* and *reactio*. Moreover, Newton himself fully realized that time and space were essential elements as physically effective factors of his system, if only

by implication. [中文](#)

This Newtonian basis proved eminently fruitful and was regarded as final up to the end of the nineteenth century. It not only gave results for the movements of the heavenly bodies down to the most minute details, but also furnished a theory of the mechanics of discrete and continuous masses, a simple explanation of the principle of the conservation of energy, and a complete and brilliant theory of heat. The explanation of the facts of electrodynamics within the Newtonian system was more forced; least convincing of all, from the very beginning, was the theory of light. [中文](#)

It is not surprising that Newton would not listen to a wave theory of light; for such a theory was most unsuited to his theoretical foundation. The assumption that space was filled with a medium consisting of material points that propagated light waves without exhibiting any other mechanical properties must have seemed to him quite artificial. The strongest empirical arguments for the wave nature of light, fixed speeds of propagation, interference, diffraction, polarization, were either unknown or else not known in any well-ordered synthesis. He was justified in sticking to his corpuscular theory of light. During the nineteenth century the dispute was settled in favour of the wave theory. Yet no serious doubt of the mechanical foundation of physics arose, in the first place because nobody knew where to find a foundation of another sort. Only slowly, under the irresistible pressure of facts, there developed a new foundation of field-physics. [中文](#)

From Newton's time on, the theory of action-at-a-distance was constantly found artificial. Efforts were not lacking to explain gravitation by a kinetic theory, that is, on the basis of collision forces of hypothetical mass particles. But the attempts were superficial and bore no fruit. The strange part played by space (or the inertial system) within the mechanical foundation was also clearly recognized, and

criticized with especial clarity by Ernst Mach.

[中文](#)

The great change was brought about by Faraday, Maxwell and Hertz—as a matter of fact half-unconsciously and against their will. All three of them, throughout their lives, considered themselves adherents of the mechanical theory. Hertz had found the simplest form for the equations of the electromagnetic field, and declared that any theory leading to these equations was Maxwellian theory. Yet towards the end of his short life he wrote a paper in which he presented as the foundation of physics a mechanical theory freed from the force-concept.

[中文](#)

For us, who took in Faraday's ideas so to speak with our mother's milk, it is hard to appreciate their greatness and audacity. Faraday must have grasped with unerring instinct the artificial nature of all attempts to refer electromagnetic phenomena to actions-at-a-distance between electric particles reacting on each other. All these electric particles together seemed to create in the surrounding space spatial states, today called fields, which he conceived as states of mechanical stress in a space-filling medium, similar to the states of stress in an elastically distended body. For at that time this was the only way one could conceive of states that were apparently continuously distributed in space. The peculiar type of mechanical interpretation of these fields remained in the background—a sort of placation of the scientific conscience in view of the mechanical tradition of Faraday's time.

[中文](#)

With the help of these new field concepts, Faraday succeeded in forming a qualitative concept of the whole complex of electromagnetic effects discovered by him and his predecessors. The precise formulation of the time-space laws of those fields was the work of Maxwell. Imagine his feelings when the differential equations he had formulated proved to him that electromagnetic fields spread in the form of polarized waves and with the speed of light! At that thrilling

moment he surely never guessed that the nature of light, apparently so completely solved, would continue to baffle succeeding generations. Meantime, it took physicists some decades to grasp the full significance of Maxwell's discovery, so bold was the leap that his genius forced upon the conceptions of his fellow-workers. Only after Hertz had demonstrated experimentally the existence of Maxwell's electromagnetic waves did resistance to the new theory break down.

[中文](#)

But if the electromagnetic field could exist as a wave independent of the material source, then the electrostatic interaction could no longer be explained as action-at-a-distance; and what was true for electrical action could not be denied for gravitation. Everywhere Newton's actions-at-a-distance gave way to fields spreading with finite velocity.

[中文](#)

Of Newton's foundation there now remained only the material mass points subject to the law of motion. But J. J. Thomson pointed out that an electrically charged body in motion must, according to Maxwell's theory, possess a magnetic field the energy of which acted precisely as does an increase of kinetic energy to the body. If, then, a part of kinetic energy consists of field energy, might that not then be true of the whole of the kinetic energy? Perhaps the basic property of matter, its inertia, could be explained within the field theory? The question led to the problem of an interpretation of matter in terms of field theory, the solution of which would furnish an explanation of the atomic structure of matter. It was soon realized that Maxwell's theory could not accomplish such a programme. Since then many men of science have zealously sought to complete the field theory by some generalization that should comprise a theory of matter; but so far such efforts have not been crowned with success. [中文](#)

For several decades most physicists clung to the conviction that a mechanical substructure would be found for Maxwell's theory. But the

unsatisfactory results of their efforts led to gradual acceptance of the new field concepts as irreducible fundamentals—in other words, physicists resigned themselves to giving up the idea of a mechanical foundation. [中文](#)

Thus physicists held to a field-theory programme. But it could not be called a foundation, since nobody could tell whether a consistent field theory could ever explain on one hand gravitation, on the other hand the elementary components of matter. In this state of affairs it was necessary to think of material particles as mass points subject to Newton's laws of motion. This was the procedure of Lorentz in creating his electron theory and the theory of the electromagnetic phenomena of moving bodies. [中文](#)

Such was the point at which fundamental conceptions had arrived at the turn of the century. Immense progress was made in the theoretical penetration and understanding of whole groups of new phenomena; but the establishment of a unified foundation for physics seemed remote indeed; and this state of things has even been aggravated by subsequent developments. [中文](#)

The development during the present century is characterized by two theoretical systems essentially independent of each other: the theory of relativity and the quantum theory. The two systems do not directly contradict each other; but they seem little adapted to fusion into one unified theory. [中文](#)

The theory of relativity arose out of efforts to improve, with reference to logical economy, the foundation of physics as it existed at the turn of the century. The so-called special or restricted relativity theory is based on the fact that Maxwell's equations (and thus the law of propagation of light in empty space) are converted into equations of the same form, when they undergo Lorentz transformation. This formal property of the Maxwell equations is supplemented by our

fairly secure empirical knowledge that the laws of physics are the same with respect to all inertial systems. This leads to the result that the Lorentz transformation—applied to space and time coordinates—must govern the transition from one inertial system to any other. The content of the restricted relativity theory can accordingly be summarized in one sentence: all natural laws must be so conditioned that they are co-variant with respect to Lorentz transformations. From this it follows that the simultaneity of two distant events is not an invariant concept and that the dimensions of rigid bodies and the speed of clocks depend upon their state of motion. [中文](#)

A further consequence was a modification of Newton's law of motion in cases where the speed of a given body was not small compared with the speed of light. There followed also the principle of the equivalence of mass and energy, with the laws of conservation of mass and energy becoming one and the same. Once it was shown that simultaneity was relative and depended on the frame of reference, every possibility of retaining actions-at-a-distance within the foundation of physics disappeared, since that concept presupposed the absolute character of simultaneity (it must be possible to state the location of the two interacting mass points "at the same time"). [中文](#)

The general theory of relativity owes its origin to the attempt to explain a fact known since Galileo's and Newton's time but hitherto eluding all theoretical interpretation: the inertia and the weight of a body, in themselves two entirely distinct things, are measured by one and the same constant, the mass. From this correspondence follows that it is impossible to discover by experiment whether a given system of co-ordinates is accelerated, or whether its motion is straight and uniform, and the observed effects are due to a gravitational field (this is the equivalence principle of the general relativity theory). It shatters the concepts of the inertial system, as soon as gravitation enters in. It may be remarked here that the inertial system is a weak point of the

Galilean–Newtonian mechanics. For there is presupposed a mysterious property of physical space, conditioning the kind of co-ordination systems for which the law of inertia and the Newtonian law of motion hold good. [中文](#)

These difficulties can be avoided by the following postulate: natural laws are to be formulated in such a way that their form is identical for co-ordinate systems of any kind of states of motion. To accomplish this is the task of the general theory of relativity. On the other hand, we deduce from the restricted theory the existence of a Riemannian metric within the time-space continuum, which, according to the equivalence principle, describes both the gravitational field and the metric properties of space. Assuming that the field equations of gravitation are of the second differential order, the field law is clearly determined. [中文](#)

Aside from this result, the theory frees field physics from the disability it suffered from, in common with the Newtonian mechanics, of ascribing to space those independent physical properties which heretofore had been concealed by the use of an inertial system. But it cannot be claimed that those parts of the general relativity theory which can today be regarded as final have furnished physics with a complete and satisfactory foundation. In the first place, the total field appears in it to be composed of two logically unconnected parts, the gravitational and the electromagnetic. In the second place, this theory, like the earlier field theories, has not yet supplied an explanation of the atomistic structure of matter. This failure has probably some connexion with the fact that so far it has contributed nothing to the understanding of quantum phenomena. [中文](#)

In 1900, in the course of a purely theoretical investigation, Max Planck made a remarkable discovery: the law of radiation of bodies as a function of temperature could not be derived solely from the laws of Maxwellian electrodynamics. To arrive at results consistent with the

relevant experiments, radiation of a given frequency had to be treated as though it consisted of energy atoms of the individual energy $h\nu$, where h is Planck's universal constant. During the years following it was shown that light was everywhere produced and absorbed in such energy quanta. In particular, Niels Bohr was able largely to understand the structure of the atom, on the assumption that atoms can have only discrete energy values, and that the discontinuous transitions between them are connected with the emission or absorption of such an energy quantum. This threw some light on the fact that in their gaseous state elements and their compounds radiate and absorb only light of certain sharply defined frequencies. All this was quite inexplicable within the frame of the theories hitherto existing. It was clear that, at least in the field of atomistic phenomena, the character of everything that happens is determined by discrete states and by apparently discontinuous transitions between them, Planck's constant h having a decisive role. [中文](#)

The next step was taken by de Broglie. He asked himself how the discrete states could be understood by the aid of the current concepts, and hit on a parallel with stationary waves, as for example in the case of the fundamental frequencies of organ pipes and strings in acoustics. True, wave actions of the kind here required were unknown; but they could be constructed, and their mathematical laws formulated, employing Planck's constant h . De Broglie conceived an electron revolving about the atomic nucleus as being connected with such a hypothetical wave train, and made intelligible to some extent the discrete character of Bohr's "permitted" paths by the stationary character of the corresponding waves. [中文](#)

Now in mechanics the motion of material points is determined by the forces or fields of force acting upon them. Hence it was to be expected that those fields of force would also influence de Broglie's wave fields in an analogous way. Erwin Schrödinger showed how this influence

was to be taken into account, re-interpreting by an ingenious method certain formulations of classical mechanics. He even succeeded in expanding the wave mechanical theory to a point where, without the introduction of any additional hypotheses, it became applicable to any mechanical system consisting of an arbitrary number of mass points, that is to say, possessing an arbitrary number of degrees of freedom. This was possible because a mechanical system consisting of n mass points is mathematically equivalent, to a considerable degree, to one single mass point moving in a space of $3n$ dimensions. [中文](#)

On the basis of this theory there was obtained a surprisingly good representation of an immense variety of facts which otherwise appeared entirely incomprehensible. But on one point, curiously enough, there was failure: it proved impossible to associate with these Schrödinger waves definite motions of the mass points—and that, after all, had been the original purpose of the whole construction.

[中文](#)

The difficulty appeared insurmountable, until it was overcome by Born in a way as simple as it was unexpected. The de Broglie–Schrödinger wave fields were not to be interpreted as a mathematical description of how an event actually takes place in time and space, though, of course, they have reference to such an event. Rather they are a mathematical description of what we can actually know about the system. They serve only to make statistical statements and predictions of the results of all measurements which we can carry out upon the system. [中文](#)

Let me illustrate these general features of quantum mechanics by means of a simple example: we shall consider a mass point kept inside a restricted region G by forces of finite strength. If the kinetic energy of the mass point is below a certain limit, then the mass point, according to classical mechanics, can never leave the region G . But according to quantum mechanics, the mass point, after a period not

immediately predictable, is able to leave the region G , in an unpredictable direction, and escape into surrounding space. This case, according to Gamow, is a simplified model of radioactive disintegration. [中文](#)

The quantum theoretical treatment of this case is as follows: at the time t_0 we have a Schrödinger wave system entirely inside G . But from the time t_0 onwards, the waves leave the interior of G in all directions, in such a way that the amplitude of the outgoing wave is small compared to the initial amplitude of the wave system inside G . The farther these outside waves spread, the more the amplitude of the waves inside G diminishes, and correspondingly the intensity of the later waves issuing from G . Only after infinite time has passed is the wave supply inside G exhausted, while the outside wave has spread over an ever-increasing space. [中文](#)

But what has this wave process to do with the first object of our interest, the particle originally enclosed in G ? To answer this question, we must imagine some arrangement which will permit us to carry out measurements on the particle. For example, let us imagine somewhere in the surrounding space a screen so made that the particle sticks to it on coming into contact with it. Then from the intensity of the waves hitting the screen at some point, we draw conclusions as to the probability of the particle hitting the screen there at that time. As soon as the particle has hit any particular point of the screen, the whole wave field loses all its physical meaning; its only purpose was to make probability predictions as to the place and time of the particle hitting the screen (or, for example, its momentum at the time when it hits the screen). [中文](#)

All other cases are analogous. The aim of the theory is to determine the probability of the results of measurement upon a system at a given time. On the other hand, it makes no attempt to give a mathematical representation of what is actually present or goes on in space and

time. On this point the quantum theory of today differs fundamentally from all previous theories of physics, mechanistic as well as field theories. Instead of a model description of actual space-time events, it gives the probability distributions for possible measurements as functions of time. [中文](#)

The new theoretical conception owes its origin not to any flight of fancy but to the compelling force of the facts of experience. All attempts to represent the particle and wave features displayed in the phenomena of light and matter, by direct recourse to a space-time model, have so far ended in failure; and Heisenberg has convincingly shown, from an empirical point of view, that any decision as to a rigorously deterministic structure of Nature is definitely ruled out, because of the atomistic structure of our experimental apparatus. Thus it is probably out of the question that any future knowledge can compel physics again to relinquish our present statistical theoretical foundation in favour of a deterministic one which would deal directly with physical reality. Logically, the problem seems to offer two possibilities, between which we are in principle given a choice. In the end, the choice will be made according to which kind of description yields the formulation of the simplest foundation, logically speaking. At the present, we are quite without any deterministic theory directly describing the events themselves and in consonance with the facts.

[中文](#)

For the time being, we have to admit that we do not possess any general theoretical basis for physics which can be regarded as its logical foundation. The field theory, so far, has failed in the molecular sphere. It is agreed on all sides that the only principle which could serve as the basis of quantum theory would be one that constituted a translation of the field theory into the scheme of quantum statistics. Whether this will actually come about in a satisfactory manner, nobody can venture to say. [中文](#)

Some physicists, among them myself, cannot believe that we must abandon, actually and for ever, the idea of direct representation of physical reality in space and time; or that we must accept the view that events in Nature are analogous to a game of chance. It is open to every man to choose the direction of his striving; and also every man may draw comfort from Lessing's fine saying, that the search for truth is more precious than its possession. 中文

(145, 920-924; 1940)

Albert Einstein: For. Mem. R. S., Institute of Advanced Study, Princeton University.

* An address, slightly abridged, delivered at the Eighth American Scientific Congress at Washington on May 15.

关于理论物理基础的思考*

爱因斯坦

爱因斯坦在他生命最后的五年中坚持认为，虽然量子力学对量子现象的描述是合理的，但却摒弃了物理学的明确性和确定性的基础。他做出了如下的结论：“世事无绝对，每个人都可以选择自己奋斗的方向；而每个人也都可以从莱辛的一句精辟的名言中得到安慰：追求真理比拥有真理更为可贵。” [英文](#)

我们所说的物理学由这样一类自然科学组成，它们的概念的定义是以测量为依据，而且其中的概念和命题也都可用数学公式表示出来。因此可以说，所有能用数学语言来表达的那部分知识，都可划归为物理学的范畴。因此随着科学的进步，物理学的范畴似乎已经扩展到只受研究方法自身所限制的程度。物理学研究的大部分工作是致力于发展物理学的各个分支，目标是对一定领域内的实践经验给予理论解释，而且其中的定律和概念都要尽可能与实践经验紧密联系。正是这样一门科学，随着它研究发展的不断专业细化，在过去的几个世纪里彻底改变了人们的现实生活方式。 [英文](#)

另一方面，人们从一开始就一直尝试寻找一个能把所有独立的科学统一起来的理论基础，这个统一的理论由最少的概念和基本关系组成，在此基础之上各个独立分支的所有概念和关系都可以通过逻辑推导产生。这就是我们探求整个物理学基础的用意所在。 [英文](#)

显而易见这个基础并不完全类似于一座建筑的基础。当然，从逻辑上讲，各条物理定律确实都是建立在这一基础之上的。然而建筑物可能在风暴或洪水过后被严重毁坏，而其基础却完好无损；但在科学领域中，相比于与实验联系较为紧密的各个具体学科而言，这一逻辑基础总是由于新经验或新知识而处于危险的境地。 [英文](#)

建立物理学统一理论基础的第一次尝试是牛顿的工作。在他的理论中，所有的内容都可归结为如下的几个概念：

(1) 具有恒定质量的质点；

(2) 任何两个质点之间存在超距作用；

(3) 质点的运动定律。

严格说来，这里并没有什么绝对的基础，因为这些明确的定律只有在引力的超距作用下才成立；而对于别的超距作用，除了作用力和反作用力相等这条定律以外，我们不能先验地得到其他任何定律。此外，牛顿自己也充分地意识到，空间和时间是他的理论体系中的根本有效因子，不过他并未明说。 [英文](#)

牛顿的基本理论被证明是卓有成效的，并且直到19世纪末，它一直被视为是物理学的终极理论。它不但解释了天体运动以及其中最详细的细节，而且也建立了描述离散物质和连续物质的力学理论，对能量守恒原理给予了简单的解释且给出了一套完整而天才的热学理论。在牛顿的理论体系中，对电动力学的事实规律的解释是比较牵强的；而到目前为止，用牛顿的理论体系进行解释的所有理论中，最令人难以信服的是对光的理论的解释。 [英文](#)

牛顿不相信光的波动论，这不足为奇；因为这个理论与他的理论基础最不相容。假定空间里充满着一种由质点组成的媒质，这些质点传递着光波但却不显示出任何力学性质，牛顿认为这个假定人为的痕迹很明显。光具有波动性的最有力的经验论据，如不变的传播速度、干涉、衍射、偏振等，这些在当时要么还不清楚，要么就是还没有被整理总结出来。牛顿坚持认为他的光的粒子论是有道理的。到了19世纪，这场争论才以波动论的胜利而告终。但是当时人们并没有严重质疑物理学建立的力学基础，这主要是因为没有找到另一种更好的基础。在不可抗拒的事实的压力之下，一种新的场物理学基础才慢慢发展起来。 [英文](#)

从牛顿时代起，所谓的超距作用的理论就一直是难以令人信服的。试图根据假想质点发生碰撞的动力学理论来解释引力而做的努力并不

少。但是所做的这些尝试都流于表面，没有得出满意的结果。另外，人们显然意识到了空间（或者惯性系）在以力学为基础的理论中有奇特的作用，而恩斯特·马赫也对此做了清楚详细的论述。

英文

法拉第、麦克斯韦和赫兹带来了物理学的伟大变革，事实上这一变革是他们在半无意的情况下做出的，并且同他们最初的意愿相悖。自始至终，这三位物理学家都认为自己是力学理论的拥护者。赫兹发现了电磁场方程最简单的形式，并且宣称任何能够导出这些方程的理论都是麦克斯韦理论。可是就在他短暂的一生结束之前，他写了一篇论文，其中他提出了一种摆脱了力这个概念的力学理论并将其作为物理学的基础。

英文

对于我们来说，接受法拉第的理论如同我们吸吮母亲的乳汁一样自然，我们很难体会到这些物理学家们的伟大和过人的胆识。对于一切试图把电磁现象归结为相互作用的带电粒子之间存在超距作用的做法，法拉第以准确无误的直觉看出了这些做法是人为不客观的。所有这些带电粒子似乎共同在其周围空间中产生了一些空间态，现在我们称之为场，法拉第设想这些空间态是当机械协强作用于充满空间的介质时出现的状态，类似于弹性膨胀体受到协强作用时的状态。因为在那个时候，为了想象这些在空间中明显是连续分布的状态，这是唯一可行的方法。这种对场的特殊的力学解释只属于那个特定的历史背景——从法拉第时代传统的力学理论的角度来看，这是对当时科学意识的一种妥协和退让。

英文

借助这些新的场的概念，法拉第成功地为他和他的先辈们所发现的复杂的电磁效应提出了一整套定性的理论概念。麦克斯韦的工作则是为这些场的时空律推导出严密的公式。当麦克斯韦建立的微分方程证明了电磁场是以偏振波的形式，并且以光速在传播着的时候，想象当时的他该有怎样的感觉呀！在那激动人心的时刻，他肯定不会想到，光的本质这个表面看来已经被完美解决了的问题，仍会继续困惑以后的好几代人。同时，物理学家们也花了几十年的时间才完全领会了麦克斯韦伟大发现的全部意义，由此可见，他的同事们要在观念上作出多么勇敢的飞跃才能接受其天才般的智慧啊。直到赫兹在实验中证实了麦克斯韦电磁波的存在以后，对这个新理论的抵制才彻底消除。

英文

如果电磁场可以独立于介质源而以波的形式存在，那么，静电相互作用就不能再解释成超距作用了；而在电的相互作用情况中是正确的东西，在引力中就也可能是正确的。渐渐地，在物理学的各个方面，牛顿的超距作用都被以有限速度传播的场所替代了。 [英文](#)

牛顿的基础理论中，只有质点的运动定律这个概念直到现在仍然保留着。但是汤姆森指出：依照麦克斯韦的理论，运动着的带电体必定具有磁场，磁场的能量正好是带电体增加的那部分动能。那么如果动能的一部分是由场能组成的，那么全部动能不也可能是这样的吗？或许作为物质基本性质的惯性，是否也能在场论中得到解释？这个问题导致了利用场论对物质进行解释的困难，该困难的解决应该会给物质原子结构提供一种解释。人们很快意识到，麦克斯韦理论不能完成这个任务。从那时起，许多科学工作者就充满热情地试图完成将包含物质的理论推广到场论当中；但是到目前为止，这种努力并没有取得圆满成功。 [英文](#)

几十年以来，大多数物理学家都坚信能为麦克斯韦理论找到更基本的力学基础。但是由于他们的努力没有得到令人满意的结果，人们逐渐将场这个新的概念作为物理学不可约化的基础——换句话说，物理学家不得已放弃了力学是物理学基础的想法。 [英文](#)

因此，后来物理学家都转而支持场论的研究体系。但是并不能把场论称为基础，因为尚不确定是否有一个统一的场论，既能解释引力，又能解释物质的基本组成成分。在这种情况下，就有必要把物质粒子看作是服从牛顿运动定律的质点。这是洛伦兹在创立其电子论的过程以及研究与运动物体电磁行为有关的理论中都采用了的假设。 [英文](#)

以上这些就是我们在世纪之交物理学基本概念的由来。当时对所有新奇现象的理解和理论方面的突破都有了极大的进展；但是建立物理学统一的基础的希望似乎仍然很渺茫；而随后的进展更是加重了这一困难。 [英文](#)

二十世纪科学发展的标志是本质上各自独立的两个理论体系：相对论和量子论。这两个体系彼此没有直接的矛盾；但是它们似乎很难融合成一个统一的理论。 [英文](#)

考虑到逻辑上的便利，科学家们对物理学基础的探究导致了相对论在世纪之交的诞生。所谓狭义的或者有限制的相对论所根据的事实是：在洛伦兹变换下，麦克斯韦方程在形式上没有变化（因而光在真空中传播的定律也一样是保持不变的）。另外，这一麦克斯韦方程组的形式上的特征可以用我们已知的十分可靠的经验来进行补充，该经验就是：在所有惯性系中，物理定律都是相同的。这导致了一个惯性系到其他任何惯性系的变换必须满足应用于时空坐标的洛伦兹变换。因此，狭义相对论的内容可以总结成一句话：一切自然规律都是有条件限制的，即它们都得具有洛伦兹协变性。由此得知，两个异地事件发生的同时性并非是绝对的，刚体的尺寸和时钟的快慢都同它们的运动状态有关。 [英文](#)

相对论的另一个结果是，在物体的速率并非远小于光速的情况下，牛顿运动定律必须做相应的修正。我们还得到了质能相当性原理，即质量守恒定律和能量守恒定律可以合并成同一个定律。注意，一旦指明了同时性是相对的，并且同参照系有关，在物理学的基础中保留超距作用的任何可能性都没有了，因为这一概念是以同时性的绝对性作为前提的（即必须能够指明“在同一时刻”两个相互作用的质点所处的位置）。

[英文](#)

广义相对论源自对一个从伽利略和牛顿时代起就已经出现的问题进行解释的尝试，迄今为止这个问题也无法用现有的任何理论进行解释：物体的惯性和重量本身是两种完全不同的概念，但却用同一个物理量（质量）进行量度。由此可以推论，我们不可能通过实验判断给定的坐标系是否在加速，或是否在做匀速直线运动，而观察到的结果最终是由引力场所决定的（这就是广义相对论的等效原理）。一旦引入了引力场，惯性系的概念就失效了。这里我们注意到，惯性系是伽利略-牛顿力学的弱点。因为引入惯性系即相当于我们预先假定物理空间具有一种神秘的性质，使得惯性定律和牛顿的运动定律在这种坐标系中仍然有效。 [英文](#)

为了避免出现上面的困难，我们可以做以下假设：在处于任何一种运动状态的坐标系中，自然规律的表达形式都是完全一样的。完善这一假设正是广义相对论的任务。另一方面，我们从狭义相对论推出时空连续区中存在黎曼度规，依照等效原理，它既描述了引力场，也描述了空

间的度规性质。假定引力的场方程是二阶的微分方程，则我们可以明确地得到与场有关的定律。

英文

除了以上的结果，相对论还使场物理学摆脱了牛顿力学中把独立的物理性质归咎于空间而出现的问题，而这个问题在相对论出现之前一直是通过引入惯性系而被隐藏起来的。但是我们现在还不能断言，当今广义相对论中被视作终极理论的那些部分是否为物理学提供了完整且令人满意的物理学基础。因为首先，相对论中所有的场都由逻辑上毫无关系的两个部分，即引力部分和电磁部分所组成。其次，跟以前的场论一样，相对论直到现在还未能对物质的原子结构给予解释。相对论的这种局限性也许同它至今对理解量子现象尚无贡献这一事实有一定的关系。

英文

1900年，在纯理论研究的过程中，马克斯·普朗克得到了一个不同寻常的发现：仅从麦克斯韦电动力学定律出发，不能推导出作为温度的函数的物体辐射定律。为了得到同相关实验一致的结果，必须把那些具有一定频率的辐射看作是由一些单个能量为 $h\nu$ 的能量子所组成，此处 h 是普朗克普适常数。随后几年，事实证明光始终都是以这样的能量子的形式产生或被吸收的。特别是尼尔斯·玻尔假定原子只能具有分立的能量值，而它们之间不连续的跃迁都同这种能量子的发射或者吸收有关，据此他能够基本上推测出原子的结构。这有助于人们理解气体状态下的元素及其化合物只能辐射和吸收具有某些特定频率的光这一事实。然而所有这些在现存的理论框架内都还无法解释。显然，至少在原子现象的领域里，所发生的每件事情的特征均由分立的状态以及分立的状态之间的不连续的跃迁决定，普朗克常数 h 在这里起着决定性的作用。

英文

进一步的工作是由德布罗意完成的。他向自己提出这样一个问题：如何借助现有的物理概念来理解这些分立的状态呢？他突然想到可以类比驻波，把分立的状态理解为如声学中管风琴和弦的基频一样的情况。虽然这里需要的这样一种波动行为还是未知的；但是用上述普朗克常数 h 应该可以构造出这种波动作用并且写出相应的数学表达式。德布罗意设想电子绕原子核的旋转是同某种有待证实的波列有关的，并且认为通过相应波的驻波特征能在一定程度上理解玻尔的“允许”轨道的分立特征。

英文

既然力学中质点的运动是由作用在质点上的力或力场所决定的，那么我们可以预测，那些力场也以类似的方式影响着德布罗意所谓的波场。欧文·薛定谔向我们展示了如何考虑以上力场对波场的影响，并用巧妙的方法重新解释了经典力学中的某些公式。薛定谔甚至不需要引入任何额外的假设就成功地将波动力学理论拓展至含有任意个质点（换句话说就是具有任意个自由度）的任何力学体系。这是可能的，因为从数学的角度来看，由 n 个质点所组成的力学系统在一定程度上可以看作是在 $3n$ 维空间里运动着的单个质点。 [英文](#)

根据以上由薛定谔建立的波动力学的理论，许多用别的理论好像完全无法理解的事实都意外地得到了完美的解释。但奇怪的是，以上理论有一个缺点：它无法将薛定谔波与质点确定的运动联系起来，而毕竟这是当初构造这整个理论的最初目的。 [英文](#)

上面提到的困难似乎是不可克服的，直到玻恩用一个意想不到的简单的方法解决了该困难。德布罗意-薛定谔波场不能被理解为时空中确实发生的事件的数学描述形式，尽管该形式肯定是同这样的事件有关系的。说得恰当些，它们实际上是我们能够从体系中获知的事物的一种数学描述。它们只能用来对这个体系所进行的一切测量结果进行统计上的说明和预测。 [英文](#)

让我举个简单的例子来说明量子力学这些普遍的特点：我们考查一个质点，它被有限大小的力束缚在一个有限的区域 G 内。如果质点的动能小于某一极限，那么根据经典力学，质点就永远不可能离开 G 这个区域。可是根据量子力学，经过一段无法直接预测的时间之后，质点却可能沿某个不确定的方向离开区域 G 而跑到周围的空间里去。按照伽莫夫的观点，这就是放射性蜕变的一个简化模型。 [英文](#)

用量子理论处理以上情况如下所示：在 t_0 时刻，薛定谔波系统完全处于 G 的区域内。但是从时间 t_0 以后，这些波沿着所有可能的方向离开 G 的内部区域，在这个过程中，往外传播的波的振幅要小于 G 区域内波系统最初的振幅。往外传播的波扩散得越远，由 G 发出的处于 G 区域内的波的振幅就越小，相应地，其强度也越小。因而只有经过无限长的时间之后由 G 发出的波才会耗尽，与此同时传播到 G 区域外的波则已持续不断地

扩散到了更大的空间。 [英文](#)

但是这种波动过程同我们刚才提到的最初的对象，即原来被包围在G内的粒子有什么关系呢？要回答这个问题，我们必须设想能对粒子进行测量的某种装置。例如，想象周围空间的某个位置上有这样一个屏幕，粒子一旦与它接触就会被粘住。于是，根据波射到屏上某个点的强度，我们就可断定粒子在那时射到屏上这一点的概率。但是一旦粒子被射到屏上的点都是特定的点时，则整个波场立即失去了所有的物理意义；这种做法唯一的目的是对粒子射到屏上的位置和时间（又或者如，粒子射到屏上时的动量）的概率做出相应的预测。 [英文](#)

所有其他的例子也都是类似的。量子理论的目的就是要确定某一时刻体系测量结果的概率。但是另一方面，它并没有试图对时空中真实存在或正在进行的事物作出相应的数学描述。在这一点上，今天的量子理论同以前所有的物理学理论，不管是力学还是场论，都有本质的区别。量子理论不是就真实时空中的事件进行模型化的描述，而是对可能的测量结果给出概率分布随时间的变化。 [英文](#)

必须承认，这个新理论的概念并不是来源于任何异想天开的想法，而是在经验事实的强制下产生的。光和物质在现象中都显示出了粒子性和波动性，所有试图借助时空模型来融合这两种性质的做法到目前为止都以失败告终。而且海森堡也给出了令人信服的观点：从经验的角度来看，由于我们的实验仪器的结构是由原子组成的，所以一定不可能出现任何与自然界严格的决定论理论结构有关的结果。因此，虽然决定论可以直接处理物理实在，但是即使是未来进一步发展的知识也不太可能使物理学放弃现在统计性的理论基础而以决定论取而代之。从逻辑上来看，这个问题似乎给出了两种可能性，原则上我们可以在这两种可能性中做出选择。最终，作为选择依据的是，所选择的描述方式要尽可能得到逻辑上最简单的物理学基础所对应的公式。目前，还完全没有任何一种决定论性的理论既能直接描述事件本身又能同事实相符合。 [英文](#)

目前我们还不得不承认，暂时还没有任何全面的物理学的基本理论可被作为物理学的逻辑基础。到现在为止，场论已经被证明不适用于分子领域。人们从各个方面进行考虑，都认为唯一可能作为量子力学根基

的原理应是一种能够把场论和量子统计学体系对应统一起来的理论。至于实际上这个原理能否以一种令人满意的方式出现，现在谁也不敢断言。 [英文](#)

有些物理学家，包括我自己在内，都不能相信：我们现在甚至将来都必须永远放弃在时空中直接表示物理实在的想法；或者我们必须接受这样的观点，即自然界中发生的事件就像碰运气的赌博一样。每个人都可以自由选择自己奋斗的方向；而每个人也都可以从莱辛的一句精辟的名言中得到安慰：追求真理比拥有真理更为可贵。 [英文](#)

（沈乃澂 翻译；葛墨林 审稿）

* 这是一篇经过删节的演讲，发表于5月15日在华盛顿举行的第八届美国科学大会。

Causality or Indeterminism?

H. T. H. Piaggio

John von Neumann had recently claimed to prove that no theory could go beyond the current quantum theory in giving a causal account of quantum physics. Thus while some physicists, such as Einstein, suspected that quantum theory might only be an approximate theory, statistical in character because it left out details of some deeper level of physical reality, von Neumann claimed that this was impossible. Henry Piaggio here reviews the arguments for and against this claim, concluding that while the balance of evidence seemed to weigh against the possibility of deterministic laws, they could not be ruled out. Many years later, von Neumann's argument would be dismantled by John Bell, who helped revitalize interest in deterministic quantum theories.

[中文](#)

A short article published in *Nature* of July 22, 1944¹, entitled “Collapse of Determinism”, contained a brief statement of von Neumann's claim to have demonstrated that the results of the quantum theory cannot be obtained by averaging any exact causal laws. If one may judge from the number of communications referring to this point which have been submitted to the Editors, many regard this claim with suspicion and desire a more detailed discussion of the grounds on which it is based. Mr. W. W. Barkas² suggested that the existence of statistical regularity when large numbers of events are

considered is incompatible with indeterminism, and that if the final result of the behaviour of a million photons were fixed, the behaviour of the first 999,000 must influence the other 1,000. Prof. (now Sir Edmund) Whittaker² replied that it might be profitable to consider the behaviour of tossed coins. He asked, in particular, whether the statistical regularity for this case, calculated by the ordinary theory of probability, involves the assumption of “crypto-determinism” (that is, real determinism hidden by lack of detailed information) or merely the assumption of symmetry. This reply produced further letters, too numerous for the Editors to publish in full, and I have been asked to give a connected account of the points raised. I shall start with the experimental evidence concerning coin-tossing, and contrast it with the theoretical discussion. After this I shall touch upon similar considerations for the kinetic theory of gases. Finally, and most important, I shall give some details of von Neumann’s supposed disproof of causality, and give the arguments for and against it. 中文

Buffon, the French naturalist, tossed a coin until he obtained 2,048 heads. The results were quoted by De Morgan³, who gave also an account of three similar experiments by his own pupils or correspondents. The arrangement by which the last toss ended with a head gave a small advantage to heads, but too small to make any significant difference. Much more extensive experiments, on somewhat different lines, were carried out by W. S. Jevons⁴, who took “a handful of ten coins, usually shillings”, and tossed the ten together. He made two series of 1,024 such tossings of ten coins, so that in each series 10,240 coins were tossed. The results of these six experiments were as follows:

No. of heads	2,048	2,048	2,048	2,048	5,222	5,131
No. of tails	1,992	2,044	2,020	2,069	5,018	5,109
Total	4,040	4,092	4,068	4,117	10,240	10,240
Excess of heads over mean	28	2	14	−10.5	102	11
Proportion of heads	0.5069	0.5005	0.5034	0.4974	0.5100	0.5011
Excess over mean	0.0069	0.0005	0.0034	−0.0026	0.0100	0.0011

If we examine these results, we see that it is easy to misinterpret the meaning of “statistical regularity”. It is certainly not true, as some correspondents seemed to think, that the numbers of heads and tails are bound to be equal. In fact, the divergence from the mean actually increased from a maximum of 28 in the first four experiments, each based on roughly 4,096 tosses, to a maximum of 102 in the last pair, each based on 10,240 tosses. This is quite in accordance with theory, which, assuming that the probability of a head in one toss is 0.5, deduces that for a large number n of tosses, it is as likely as not that the divergence from the expected mean $n/2$ will exceed $0.3372\sqrt{n}$, but it is almost certain (99.73 percent probability) that it will be less than $1.5\sqrt{n}$. For $n = 4,096$ the “as-likely-as-not divergence” is, to the nearest integer, 22, and the “scarcely-ever divergence” is 96. For $n = 10,240$, the corresponding numbers are 34 and 152. Thus the actual divergences, though larger and more one-sided than some might have expected, are quite compatible with the theory. But the phrase “statistical regularity” really refers to the *proportion* of heads, which, according to theory, should be very nearly 0.5, with an “as-likely-as-not divergence” of $0.3372\sqrt{n}$ and a “scarcely-ever divergence” of $1.5/\sqrt{n}$. Both these divergences diminish indefinitely as n increases. We may also estimate the theoretical divergence of the proportion by its root-mean-square or “standard deviation”. This has the value $0.5/\sqrt{n}$, a result which we shall contrast later with Heisenberg’s Principle of Uncertainty. 中文

We now come to an important criticism of the theory of probability on which the above calculations are based. As pointed out by Lieut.-Colonel E. Gold⁵, there is an assumption of symmetry, not only in the two faces of the coin, but also in the actions of the hand that tosses the coin. When the hand was replaced by a machine, such as that devised by J. Horzelski⁶, the absence of this symmetry was manifest.

By a certain adjustment of the pressure actuating a lever, he obtained 98 heads out of 100 tosses. He then slightly altered the pressure, keeping the head, as before, initially upwards on the machine, and obtained only one head in the next 100 tosses. In this case the tossing mechanism is not a hidden parameter, but is visible and definite, whereas in the usual tossing it is indefinite and, so far as we can manage it, symmetrically distributed. It is possible that the excess of heads in Jevons's experiments was due to some slight lack of symmetry in his tossing conditions. Whether this was so or not, it appears obvious that *the description of reality given by the theory of probability in coin-tossing is not complete.* 中文

It is therefore erroneous to suppose that the properties of a perfectly normal distribution must necessarily correspond exactly with physical reality, however useful they may be in giving a good approximation to the facts. We cannot disprove the existence of the details of the projection merely by claiming that they upset the purity of the normal distribution. It is rather the very purity of that distribution which goes beyond the physical facts, and so is not a complete description of reality. Similar considerations apply to the kinetic theory of gases, but in this case the symmetry assumed in the theory⁷ is a much closer approximation to the actual facts. But it is only an approximation, and here, as elsewhere in classical physics, pure statistical aggregates do not exist. 中文

This brings us to the question whether such aggregates exist in non-classical physics, in particular in quantum mechanics. We shall examine von Neumann's arguments, using for this purpose not only his well-known treatise "Mathematische Grundlagen der Quantenmechanik" (1932), but also the shorter account, in English, that he gave in Warsaw⁸ in 1937, and the discussion that ensued. The starting point is an analysis of the qualitative laws obeyed by the mathematical "hypermaximal projective" operators which correspond

to the physical quantities occurring in quantum mechanics. Everything is said to be based on six laws, of which two seem more important than the rest. One is the principle of superposition, extended to quantities not necessarily simultaneously measurable. The other may be called the principle of exact functional correspondence; for example, if an operator represents a physical quantity, then the square of the operator represents the square of the quantity. 中文

In my opinion, however, the emphasis on these simple laws conceals the fact that other conditions of greater importance are imposed by the definition of “hypermaximal projective” operators. This definition implies some characteristic results of quantum mechanics, and the simple laws are merely the final requirements. Von Neumann shows that aggregates are of two kinds, “pure” and “mixed”. The essential property of a pure aggregate is that it cannot be regarded as a mixture of two other non-identical aggregates. The qualitative laws of quantum mechanics show that the aggregates concerned must be pure, whereas all aggregates based upon causal laws, such as tossed coins or gas particles, must be mixed. Hence, he concludes, causality is incompatible with quantum mechanics, and the process of averaging causal laws, as applied in the kinetic theory of gases, cannot possibly be extended to quantum mechanics. There is no need, he says, to go more deeply into the details of a supposed system which is governed by further conditions (“hidden parameters”) in addition to the wave functions. These hidden parameters would upset the qualitative laws of quantum mechanics. He admits that quantum mechanics in its present form is certainly defective, and, in spite of its great success in explaining physical phenomena, may possibly, in the long run, turn out to be false. But this is true of every theory; we can never say that it is proved by experiment, but only that it is the best summing up of experiment at present known. 中文

Von Neumann therefore concludes that there is at present no reason

and no excuse for supposing the existence of causality in quantum mechanics. This conclusion is described by Whittaker⁹ as not only novel and unexpected, but also almost incredible, yet he endorses it with the exultant declaration “the bonds of necessity have been broken; for certain classes of phenomena, crypto-determinism is definitely disproved”. [中文](#)

Other comments have been more sceptical. At the Warsaw conference, the president, C. Bialobrzski, after hearing von Neumann, admitted the validity of the argument that it was impossible to fit causality into the framework of quantum mechanics, but expressed a doubt as to the logical coherence of that framework. In his opinion it is deficient because it does not take account of irreversible changes, and also because, in certain conditions of measurement, the indeterminism of the final state disappears, and the assumptions of discontinuity and indeterminism do not correspond to reality. He thought it necessary to introduce a new postulate concerning measurement. At a later meeting of the same conference a letter from Heisenberg said that the quantum theory, in its present form, could not yet give a logically coherent account of nuclear physics or of cosmic rays. [中文](#)

Many critics are suspicious of purely abstract arguments which make no reference to experiment. Of course, such experiments as those of Davisson and Germer on electron diffraction and of Condon and Gurney on radioactivity, though excellent as illustrations of the Uncertainty Principle, yet have no value in deciding whether this uncertainty is due only to lack of detailed knowledge, or to true indeterminism. On a somewhat different plane is the argument of Whittaker⁹, who, though a supporter of von Neumann, illustrates his argument by a reference to the passage of plane-polarized light passing through a Nicol prism, and shows that the phenomena cannot be explained by causal laws governing any hidden parameters attributed to the photons. However, H. Pelzer¹⁰ gives two models in

which hidden parameters, attributed at least partly to the Nicol prism, can exist and obey causal laws. From this he infers that the arguments of Whittaker and von Neumann are incomplete, even though he agrees with their conclusion that quantum phenomena are truly indeterminate. [中文](#)

My own criticism of von Neumann is founded upon a paper by A. Einstein, B. Podolsky and N. Rosen¹¹. By considering the problem of making predictions concerning a system on the basis of measurements made on another system which had previously interacted with it, they conclude that *the description of reality as given by a wave function is not complete*. As a wave function is a mathematical way of representing a probability distribution, this conclusion is almost exactly the same as that which I enunciated concerning coin-tossing. I therefore, with great diffidence, offer the opinion that the existence of causality has *not* been disproved. It is true that Einstein's opinion has been rejected by N. Bohr¹², but there are other grounds for supporting it. In fact, the postulate of quantum mechanics that electrons cannot be distinguished from one another appears, at least to me, not to be a statement that Nature is incomprehensible, but merely that quantum mechanics is incomplete. However, I do not wish to insist that there is no difference between coin-tossing and quantum mechanics. One striking difference is that in coin-tossing the standard deviation of the proportion of heads depends only upon the number of tosses, and can be diminished indefinitely; but in quantum mechanics the Principle of Uncertainty gives for the product of the standard deviations of the momentum and displacement a minimum value, namely, $h/4\pi$. The occurrence of Planck's constant in this result seems to show that there is something essentially new. I should find it easier to accept von Neumann's conclusions if his arguments, instead of being purely qualitative, contained this constant. Perhaps it is really concealed somewhere in the background, like a hidden parameter! [中文](#)

To conclude, I will quote the opinion expressed by Bertrand Russell¹³ in 1936, that at present there is no decisive reason in favour of complete determinism (causality) in physics, but that there is no reason against it, and that it is theoretically impossible that there should be any such reason. But Russell does not mention von Neumann's arguments. My own conclusion is that the balance of the present evidence is rather against complete causality, but that the question is still unsettled. 中文

(155, 289-290; 1945)

H. T. H. Piggio: University College, Nottingham.

References:

1. *Nature*, **154**, 122 (1944).
2. *Nature*, **154**, 676 (1944).
3. "Budget of Paradoxes", 170 (1872).
4. "Principles of Science", 238 (1874); or 2nd ed., 208 (1877).
5. *Nature*, **155**, 111 (1945).
6. *Nature*, **155**, 111 (1945).
7. Preston, "Theory of Heat", 4th ed., 782 (1929).
8. "New Theories in Physics", 30-45.
9. *Proc. Phys. Soc.*, **55**, 459 (1943).
10. *Proc. Phys. Soc.*, **53**, 195 (1944).
11. *Phys. Rev.*, **47**, 777 (1935).
12. *Phys. Rev.*, **48**, 696 (1935).
13. *Proc. Univ. of Durham Phil. Soc.*, **9**, 228 (1936).

因果律还是非决定论？

皮亚焦

约翰·冯·诺伊曼最近宣称，他将证明在对量子物理给出的因果解释方面没有任何一个理论能够超过当今的量子理论。虽然一些物理学家，例如爱因斯坦，认为量子理论也许仅仅是一个近似理论，具有统计特征，因为它忽视了物理现实中某些更深层次的细节，但冯·诺伊曼却不这样认为。在这篇文章中，亨利·皮亚焦对这两种不同的观点进行了评论，最后得出结论：虽然证据不利于决定论，但也不能将其完全排除。许多年以后，约翰·贝尔又推翻了冯·诺伊曼的观点，这使得人们开始再次关注决定论的量子理论。 [英文](#)

发表在1944年7月22日《自然》上的一篇题为《决定论的崩溃》的短文^[1]，简单地描述了冯·诺伊曼的观点，即不能通过对一些精确的因果规律取平均来得到量子理论的结果。如果仅从编辑部收到的关注这一观点的信函的数量来看，我们发现很多人都对这一观点表示怀疑，并且希望能就这一观点建立的基础进行更详细的讨论。巴卡斯^[2]先生认为，当考虑大量的事件时，统计规律与非决定论是不相符的，他还提到，如果100万个光子的最终行为结果是确定的，那么，前999,000个光子的行为必定会影响另外1,000个光子的行为。惠特克^[2]教授（现在是埃德蒙爵士）对此的回应是：我们也许可以分析一下抛掷硬币的行为。他特别问道，对于抛掷硬币来说，根据一般的概率理论计算出来的统计规律是涉及了“隐秘决定论”（即由于缺乏详细信息而隐藏了真正的决定论）的假设，还是仅与对称性假设有关。这一回应又引发了很多评论文章，因其数量太多致使编辑部很难将其全部发表，而且我也被要求针对这些观点给出有关的解释。我将从抛掷硬币的实验结果开始谈起，并将它与理论值进行比较。之后，我也将对气体的动力学理论作相似的分析。最后，也是最为重要的，我将详细解释冯·诺伊曼对于因果律的假设反驳，并且

给出支持和反对它的理由。

英文

法国博物学家布丰不停地抛掷一枚硬币，直到他得到2,048次正面朝上为止。德·摩尔根^[3]引证了这一结果，并介绍了由他的学生或相关人员完成的3个与之相似的实验。这种规定以正面朝上为结束的抛掷实验让正面朝上的结果略占优势，但是，这个优势太小以至于可以忽略不计。杰文斯^[4]以稍为不同的方式进行了更为广泛的实验，他以“10个硬币（通常是面额为1先令的硬币）作为一组”，并一起抛掷。他做了两个系列的实验，各含1,024次这种10个一组的抛掷，因此每个系列中都抛掷了10,240个硬币。上述6个实验的统计结果如下：

正面朝上次数	2,048	2,048	2,048	2,048	5,222	5,131
反面朝上次数	1,992	2,044	2,020	2,069	5,018	5,109
总次数	4,040	4,092	4,068	4,117	10,240	10,240
正面朝上次数超过平均数的量	28	2	14	-10.5	102	11
正面朝上的比例	0.5069	0.5005	0.5034	0.4974	0.5100	0.5011
正面朝上的比例超过 50% 的量	0.0069	0.0005	0.0034	-0.0026	0.0100	0.0011

英文

如果我们查看这些统计数字，就很容易曲解“统计规律”的含义。有些人认为，正面朝上和反面朝上的次数一定会是相等的，这显然是不正确的。实际上，前4个实验都抛掷了约4,096次，正面朝上的次数超过平均数的最大值为28，而最后2个实验各抛掷了10,240次，其最大值为102，因此，偏离平均数的差值实际上是在增加的。这一点同理论吻合得非常好，理论认为，在一次抛掷硬币的过程中，正面朝上的概率为0.5，据此推断，如果抛掷 n （一个很大的数字）次硬币，那么偏离预期平均值 $n/2$ 的差值很可能会超过 $0.3372\sqrt{n}$ ，但是几乎可以肯定（99.73%的可能性）该值会小于 $1.5\sqrt{n}$ 。当 $n = 4,096$ 时，“很可能的偏差”最接近整数22，而“几乎不可能出现的偏差”是96。当 $n = 10,240$ 时，相应的值为34和152。因此，尽管实际的偏差要比一些人预期的大且不均衡，但与这个理论还是非常一致的。但是，根据理论，“统计规律”这个短语真正的意义指的是正面朝上出现的比例应该非常接近0.5，其“很可能的偏差”为 $0.3372\sqrt{n}$ ，“几乎不可能出现的偏差”为 $1.5/\sqrt{n}$ 。随着 n 的增加，这两个偏差都会无限地减少。我们也可以根据这个比例的均方根或“标准偏差”来估算其理论偏差。得到的值为 $0.5/\sqrt{n}$ ，稍后我们会将这一结果与海森堡的测不准原理进行比较。

英文

现在我们来讨论一下上面计算所依据的概率理论的一个重要的不妥之处。正如陆军中校戈尔德^[5]指出的，对称性的假设不仅存在于硬币本身的正反两面，而且还存在于抛掷硬币时手的动作。当用机器取代手时，比如霍莱斯基^[6]设计的机器，实验结果就出现了明显的不对称性。通过对驱动杠杆的压力进行适当调节，在抛掷100次硬币后，他得到了98次正面朝上的结果。接着，他轻微地改变了压力，初始时硬币在机器上同样保持正面朝上，但在接下来的100次抛掷中，只得到了一次正面朝上的结果。在这种情况下，抛掷机制不是一个隐藏的参数，而是可见并且确定的参数，而在一般的抛掷情况下，这个参数是不确定的，而且在我们所能控制的范围内，它就是对称分布的。在杰文斯的实验中，正面朝上的情况太多很可能是因为抛掷情况缺乏对称性。不管情况是否如此，很明显，在抛掷硬币的实验中，概率理论给出的事实描述是不完善的。

[英文](#)

因此，认为完美正态分布的性质必定严格符合物理现实是错误的，不过通常情况下这些性质可以为事实提供一个很好的近似。我们不能仅仅通过宣称抛掷细节搅乱了正态分布的纯正性，从而否认这些细节的存在。事实上，正是因为分布太过纯正，超出了物理的现实，因此，它才不是对现实的完整描述。同样的道理也适用于气体的动力学理论，但在这种情况下，该理论中^[7]的对称性假设更接近于实际的事实。但仅仅只是接近而已，就像在经典物理学的其他地方一样，在这里纯粹的统计集合是不存在的。

[英文](#)

这使我们遇到这样一个问题，即这样的集合是否也存在于非经典物理学中，特别是量子力学之中呢？为了得到解答，我们将查证冯·诺伊曼的观点，其中不仅涉及他的著作《量子力学的数学基础》（1932年），还涉及他于1937年在华沙^[8]用英文写的简短解释和对此所作的进一步的讨论。其起始点是对数学的“超大投影”算符所遵循的定性法则的分析，该算符与量子力学中出现的物理量相对应。一切都基于六条法则，其中有两处似乎尤为重要。一条是叠加原理，它适用于不必同时测量的物理量。另一条是严格的函数对应性原理；比如说，如果一个算符代表一个物理量，那么算符的平方就代表这个物理量的平方。

[英文](#)

然而在我看来，过分注重这些简单的法则使我们忽视了通过“超大投

影”算符的定义所带来的其他一些更为重要的条件。这个定义暗含了量子力学的一些特定结果，并且这些简单的法则仅仅是最后的必要条件。冯·诺伊曼认为集合分为“纯集合”和“混合集合”两种。纯集合的主要性质是它不能被表示为两个不同集合的混合。量子力学的定性法则表明与其有关的集合必然是纯集合，而如抛掷硬币或气体粒子等所有服从因果论的集合都必然是混合的。因此他得出结论：因果论与量子力学是不兼容的，并且在气体动力学理论中用到的平均因果论的方法不能应用于量子力学。他认为，对于一个受波函数控制以外还受其他条件（“隐参量”）控制的设定系统，没有必要去深究细节。这些隐参量将会打乱量子力学的定性法则。他承认当时的量子力学的确是有缺陷的，尽管它在解释物理现象方面取得了巨大的成功，但以后仍然有可能被证明是错误的。不过，每一个理论都是这样的；我们永远不可能声称用实验证明了它，只能说目前这是对实验的最好总结。 英文

因此，冯·诺伊曼得出结论：目前在量子力学中没有任何理由能够推测出因果律的存在。惠特克^[9]认为这个结论不仅是新奇且出人意料的，而且几乎是令人难以置信的，他还用兴奋的语言对其表示认同，“必然性的联系已被打破；对于某几类现象，隐秘决定论将完全被推翻”。

英文

其他评论则对此持有更多的怀疑。在华沙会议上，会议主席比亚洛布尔泽斯基在听取了冯·诺伊曼的演讲后，承认现在确实不可能将因果律纳入量子力学的理论框架中，但他对这一理论框架的逻辑连贯性提出了质疑。他认为，由于没有考虑到不可逆变化，也由于在一定的测量条件下终态的不确定性消失了，而且不连续性和不确定性的假想与现实并不相符，所以这是有缺陷的。他认为有必要根据测量提出一个新的假定。在会议后期的一个会上，海森堡在一封来信中说，当前的量子理论还无法为核物理学或宇宙射线给出一个逻辑一致的解释。 英文

许多评论家都质疑这些没有实验作为依托的完全抽象的理论观点。当然，尽管像戴维孙和革末在电子衍射方面的实验以及康登和格尼在放射性方面的实验都对测不准原理进行了完美的阐释，但是人们依旧无法说明这个不确定性究竟只是因为缺乏具体知识还是确实无法确定。惠特克^[9]从一个稍微不同的角度阐述了自己的观点，惠特克是冯·诺伊曼的支

持者，但是他通过引用一篇平面偏振光通过尼科尔棱镜的文章来表明，这种现象不能用控制着由光子引起的一些隐参量的因果律来解释。但是佩尔泽^[10]给出了两个模型，其中的隐参量能够存在并遵循因果律，而这些隐参量至少部分来源于尼科尔棱镜。从这点他得出推断：惠特克和冯·诺伊曼的观点是不完整的，尽管他也认同他们关于量子现象确实不可确定的结论。 [英文](#)

我对冯·诺伊曼的批判基于一篇由爱因斯坦、波多尔斯基和罗森^[11]共同撰写的论文。他们基于对曾经与该系统发生过相互作用的另一系统的测量来考虑对该系统进行预测的问题，他们得出的结论是：仅仅用波函数来描述现实世界是不完整的。因为波函数只是描述概率分布的一种数学方法，这个结论和我对于抛掷硬币实验所得的结论几乎完全一样。因此我非常不自信地提出：因果律的存在还没有完全被否认。爱因斯坦的观点确实已经被玻尔^[12]推翻，但还是存在一些其他依据来支持它。事实上，量子力学中关于电子与电子间无法区分的假设出现了，至少对我来说，这并不表明大自然是不可理解的，它仅仅说明量子力学是不完整的。但我并非想说量子力学与抛掷硬币没有任何区别。两者之间一个很明显的不同是在抛掷硬币中正面朝上的比例的标准偏差仅取决于抛掷的次数，并且可以无限减小；但是在量子力学中测不准原理给出了动量与位移的标准偏差的乘积的最小值，即 $h/4\pi$ 。这个结果中普朗克常数的出现似乎说明有一些新的东西尚待挖掘。我觉得如果冯·诺伊曼的结论中也包含这个常数，而不仅仅是一些完全定性的分析的话，我们将更容易接受他的结论。当然，也许在其背景理论中也存在像隐参量一样的某个常数！ [英文](#)

综上所述，我将引用伯特兰·罗素^[13]在1936年表述的观点：目前尚没有强有力的理由支持物理学中的完全决定论（因果律），但也没有任何理由反对它，并且理论上也不会存在这种理由。但是罗素没有提到冯·诺伊曼的观点。我的结论是现在的证据不利于完全的因果律，但是这个问题依旧没有被彻底解决。 [英文](#)

（刘霞 翻译；赵见高 审稿）

Processes Involving Charged Mesons

C. M. G. Lattes *et al.*

César Lattes and colleagues from the University of Bristol here report recent results from cosmic-ray experiments suggesting the existence of hitherto unknown particles. They had found that some particles having masses small compared to the proton could cause nuclear disintegrations involving the emission of several heavy particles. They referred to the particles as mesons, this being the accepted term for any particle of mass intermediate to the electron and proton. Lattes and colleagues detected the particles from their unusual tracks on photographic plates, showing occasional decays of these mesons into secondary mesons. The primary mesons were later identified as the positive and negative charged pi mesons (pions), which would be created in the laboratory in a few years. [中文](#)

IN recent investigations with the photographic method^{1,2}, it has been shown that slow charged particles of small mass, present as a component of the cosmic radiation at high altitudes, can enter nuclei and produce disintegrations with the emission of heavy particles. It is convenient to apply the term “meson” to any particle with a mass intermediate between that of a proton and an electron. In continuing our experiments we have found evidence of mesons which, at the end of their range, produce secondary mesons. We have also observed

transmutations in which slow mesons are ejected from disintegrating nuclei. Several features of these processes remain to be elucidated, but we present the following account of the experiments because the results appear to bear closely on the important problem of developing a satisfactory meson theory of nuclear forces. [中文](#)

In identifying the tracks of mesons we employ the method of grain-counting. The method allows us, in principle³, to determine the mass of a particle which comes to the end of its range in the emulsion, provided that we are correct in assuming that its charge is of magnitude $|e|$. We define the “grain-density” in a track as the number of grains per unit length of the trajectory. Knowing the range-energy curve for the emulsion⁴, we can make observations on the tracks of fast protons to determine a calibration curve showing the relation between the grain-density in a track and the rate of loss of energy of the particle producing it. With this curve, the observed distribution of grains along the track of a meson allows us to deduce the total loss of energy of the particle in the emulsion. The energy taken in conjunction with the observed range of the particle then gives a measure of its mass. [中文](#)

We have found that the above method gives satisfactory results when, in test experiments, it is applied to the determination of the mass of protons by observations on plates developed immediately after exposure. The errors in the observed values, based on grain-counts along individual tracks, are only a little greater than those corresponding to the statistical fluctuations associated with the finite number of grains in a track. As we have previously emphasized, however, serious errors arise when the method is applied to the plates exposed for several weeks to the cosmic rays². These errors are due mainly to the fading of the latent image in the time elapsing between the passage of the particle and the development of the plate. [中文](#)

We have attempted to allow for fading by determining a calibration

curve for each individual plate by grain-counts on the tracks of a number of protons, chosen at random from those originating in "stars". Such a calibration curve corresponds to an average value of the fading of the tracks in the plate. While we thus obtain improved mean values for the mass of particles of the same type, as shown by test measurements on the tracks of protons other than those used in making the calibration, the individual values are subject to wide variations. In no case, however, have mass determinations by grain-counts of particles, judged to be protons from the frequency of the small-angle scattering, given values exceeding $2,400 m_e$ or less than $1,300 m_e$. 中文

In these circumstances it is not possible to place serious reliance on the masses of individual mesons determined by grain-counts; and we employ the method, in the present experiments, only to distinguish the track of a meson from that of a proton. In searching a plate, an experienced observer quickly learns to recognize the track of a meson by inspection, provided that its range in the emulsion exceeds 100μ . Nevertheless, we regard it as established that a particular track was produced by a meson only if both the grain-density and the frequency of the Coulomb scattering correspond to the values characteristic of a particle of small mass. We have considered the possibility that as a result of a rare combination of circumstances we might, in spite of the above precautions, wrongly attribute the track of a proton to a meson of mass less than $400 m_e$. It is difficult to give a numerical estimate of the probability of making such an error, but we believe it to be very small. 中文

Secondary Mesons

We have now made an analysis of the tracks of sixty-five mesons which come to the end of their range in the emulsion. Of these, forty show no evidence for the production of a secondary particle. The remaining twenty-five lead to the production of secondary particles.

Fifteen of them produce disintegrations with the emission of two or more heavy particles, and from each of the remaining ten we observe a single secondary particle. Of these latter events, the secondary particle is in four cases a hydrogen or heavier nucleus; in four other cases the identification is uncertain, and in the last two cases it is a second meson. 中文

Fig. 1 is a reproduction of a mosaic of photomicrographs which shows that a particle, m_1 , has come to the end of its range in the emulsion. The frequent points of scattering and the rapid change of grain-density towards the end of the range show that the track was produced by a meson. It will be seen from the figure that the track of a second particle, m_2 , starts from the point where the first one ends, and that the second track also has all the characteristics of that of a particle of small mass. A similar event is shown in Fig. 2. In each case the chance that the observation corresponds to a chance juxtaposition of two tracks from unrelated events is less than 1 in 10^9 . 中文

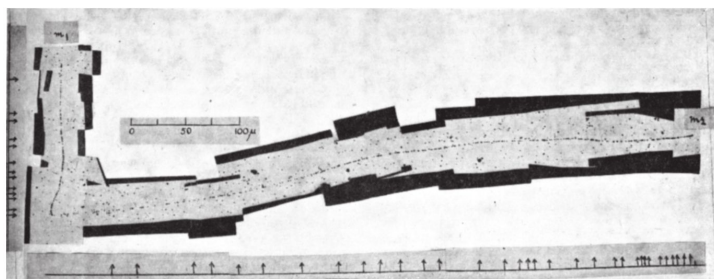


Fig. 1. Observation by Mrs. I. Roberts. Photomicrograph with Cooke $\times 45$ "fluorite" objective. Ilford "Nuclear Research", boron-loaded C2 emulsion. m_1 is the primary and m_2 the secondary meson. The arrows, in this and the following photographs, indicate points where changes in direction greater than 2° occur, as observed under the microscope. All the photographs are completely unretouched 中文

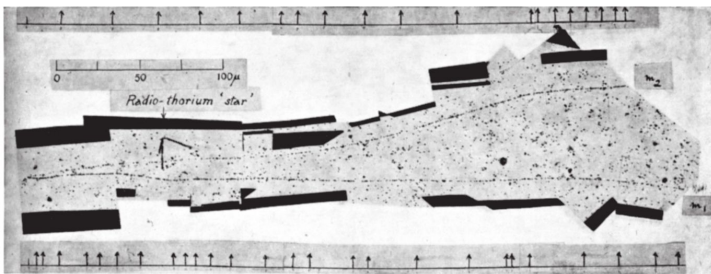


Fig. 2. Observation by Miss M. Kurz. Cooke $\times 45$ "fluorite" objective. Ilford "Nuclear Research" emulsion, type C2, boron-loaded. The secondary meson, m_2 , leaves the emulsion

中文

Grain-counts indicate that the masses of the primary particles in Figs. 1 and 2 are 350 ± 80 and $330 \pm 50 m_e$, respectively; and of the secondary particle in Fig. 1, $330 \pm 50 m_e$, the limits of error corresponding only to the standard deviations associated with the finite numbers of grains in the different tracks. All these values are deduced from calibration curves corresponding to an average value of the fading in the plate, and they will be too high if the track was produced late in the exposure, and too low if early. We may assume, however, that the two-component tracks in each event were produced in quick succession and were therefore subject to the same degree of fading. In these circumstances the measurements indicate that if there is a difference in mass between a primary and a secondary meson, it is unlikely that it is of magnitude greater than $100 m_e$. The evidence provided by Fig. 2 is not so complete because the secondary particle passes out of the emulsion, but the variation in the grain density in the track indicates that it was then near the end of its range. We conclude that the secondary mesons were ejected with nearly equal energy.

中文

We have attempted to interpret these two events in terms of an interaction of the primary meson with a nucleus in the emulsion which leads to the ejection of a second meson of the same mass as the first. Any reaction of the type represented by the equations

$$A_Z^N + \mu_{-1}^0 \rightarrow B_{Z-2}^N + \mu_{+1}^0 \text{ or } A_Z^N + \mu_{+1}^0 \rightarrow C_{Z+2}^N + \mu_{-1}^0, \quad (1)$$

in which A represents any stable nucleus known to be present in the emulsion, involves an absorption of energy, in contradiction with the fact that the secondary meson is observed to have an energy of about 2 MeV. [中文](#)

A second process, represented by the equation

$$\text{Ag}_7 + \mu_{-1}^0 \rightarrow X_Z + Y_{45-Z} + \mu_{+1}^0, \quad (2)$$

in which X and Y represent two nuclei of approximately equal charge number, may be energetically possible, but the chance of it occurring in conditions where the total energy of the two recoiling nuclei is of the order of only a few million electron-volts is remote. It is therefore possible that our photographs indicate the existence of mesons of different mass^{5,6,7}. The evidence provided by grain counts is not inconsistent with such an assumption. We have no direct evidence of the signs of the charges carried by the two mesons, except that the one secondary meson which comes to the end of its range in the emulsion does not lead to a disintegration with the emission of heavy particles. If, however, we assume that the transmutation corresponds to the interaction of the primary meson with a light nucleus, of a type represented by the equation

$$\text{C}_6^{12} + \mu_{-1}^0 \rightarrow \text{Be}_4^{12} + \mu_{+1}^0, \quad (3)$$

the difference in mass of the two mesons must be of the order of 60 m_e , according to estimates of the mass of the beryllium nucleus. [中文](#)

The only meson theory, to our knowledge, which assumes the existence of mesons of different mass is that of Schwinger⁸. It is visualized⁹ that a negative vector meson should have a very short life and should lead to the production of a pseudo-scalar meson of the same charge but lower mass, together with a quantum of radiation. It will therefore be of great interest to determine whether the secondary

meson, in transmutations of the type we have observed, is always emitted with the same energy. If this is so, we must assume that we are dealing with a more fundamental type of process than one involving particular nuclei such as is represented in equation (3). If, as an example of such a process, we assume that the momentum of the secondary meson appearing in our experiments is equal and opposite to that of an emitted photon, the total release of energy in the transmutation is of the order of 25 MeV. [中文](#)

In recent communications^{10,11} very radical conclusions have been drawn from the results of observations on the delayed coincidences produced by positive and negative mesons in interactions with light and heavy nuclei^{12,13}. It is assumed that a negative meson, at the end of its range, falls into a *K* orbit around a nucleus. In the case of a heavy nucleus, it is then captured, giving rise to a disintegration with the emission of heavy particles. With a light nucleus, on the other hand, it is regarded as suffering β -decay before being captured, so that, like a positive meson, it can produce a delayed coincidence. The conclusion is drawn that the nuclear forces are smaller by several orders of magnitude than has been assumed hitherto. Since our observations indicate a new mode of decay of mesons, it is possible that they may contribute to the solution of these difficulties. [中文](#)

Emission of Mesons from Nuclei

Fig. 3 shows a mosaic of photomicrographs of a disintegration in which six tracks can be distinguished radiating from a common centre. The letters at the edge of the mosaic indicate whether a particular track passes out of the surface of the emulsion, *s*, into the glass, *g*, or ends in the emulsion, *e*. The grain-density in tracks *a* and *c* indicate that the time between the occurrence of the disintegration and the development of the plate was sufficiently short to avoid serious fading of the latent image. [中文](#)

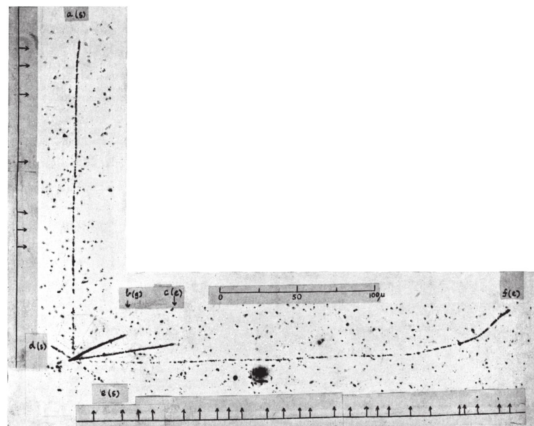


Fig. 3. Observation by Mrs. I. Roberts. Photomicrograph with Cooke $\times 45$ “fluorite” objective. Ilford “Nuclear Research”, boron-loaded C2 emulsion. The track (b) dips steeply and its apparent grain density is greater than the true value through foreshortening. Both (b) and (c) were probably produced by α -particles 中文

The track marked f suffers frequent changes in direction due to scattering, and there is a very rapid change in the grain-density in moving along the trajectory. These two features, taken together, make it certain that the track was produced by a light particle, and grain counts give an estimate for the mass of $375 \pm 70 m_e$ ¹⁴. 中文

We have now observed a total of 1,600 disintegration “stars”, in each of which three or more charged particles are ejected from a nucleus. Of these, 170 correspond to the liberation of an amount of energy equal to, or greater than, that in the “star” represented in Fig. 4, but only in two cases can we identify an emitted particle as a meson. We cannot conclude, however, that the emission of mesons in such disintegrations is so rare as these figures suggest. If a meson is emitted with an energy greater than 5 MeV., it is likely to escape detection in the conditions of our experiments. Mr. D. H. Perkins, of the Imperial College of Science and Technology, has shown that, in the B_1 emulsion, the grain-density in the track of a meson becomes very small at energies greater than 2 MeV., and we must anticipate a similar result in the C_2 emulsion at higher energies. Our observations are therefore not inconsistent with the view that the ejection of

mesons is a common feature of the disintegration of nuclei by primary particles of great energy, and that the present instance, in which the velocity of ejection has been exceptionally low so that an identification of the particle has been possible, is a rare example. It is possible that the example of meson production recently described¹⁵ is due to a similar process, produced by a primary particle of higher energy, in which some of the heavier fragments emitted on the disintegration have escaped detection because of the depth inside the lead plate at which the event occurred. 中文

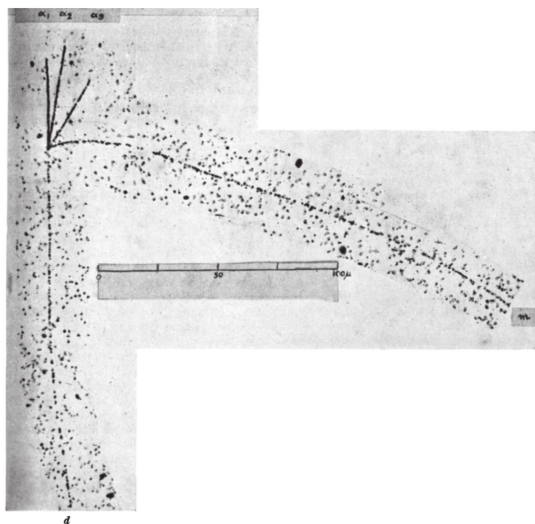


Fig. 4. Observation by Mrs. I. Roberts. Cooke $\times 95$ achromatic objective. Ilford "Nuclear Research" emulsion, type C2, lithium-loaded 中文

The disintegration shown in Fig. 3 may be the representative of a type, common in the high atmosphere with particles of great energy. In the present instance the energy of the primary particle must have been of at least 200 MeV., and, if its mass was equal to or less than that of a proton, it would not have been recorded by the emulsion.

中文

Disintegrations Produced by Mesons

The observation of the transmutations of nuclei by charged mesons

has led to the suggestion of a method for determining the mass of these particles based on observations of the total energy released in the disintegration^{1,2}. In attempting to apply the method, we meet the difficulty of identifying the particular type of nucleus undergoing disintegration and of taking account of any ejected neutrons which will not be recorded by the emulsion. A photograph of such a disintegration which, at first sight, appears to allow us to draw definite conclusions, is shown in Fig. 4. In the photograph, the tracks of four heavy particles can be distinguished, of which the short tracks α_1 , α_2 and α_3 end in the emulsion; α_1 and α_2 were certainly produced by α -particles, and grain-counts show that α_3 is due to a proton. The observations are therefore consistent with the equation



or, less probably, to a similar equation involving the emission of a deuteron or a triton in addition to the particles of short range. 中文

Grain-counts on the track of the particle of long range, d , which passes out of the emulsion, indicate that if it was produced by a proton, the initial energy of the particle was about 15 MeV. Alternatively, if the particle was a deuteron, its energy was 30 MeV.; or, if a triton, 45 MeV. In any case, we can determine the minimum energy which must be attributed to the emitted neutrons if momentum is to be conserved in the disintegration. As a result, we find a minimum value for the mass of the primary meson of $240 m_e$. The value determined by grain-counts is also $240 \pm 50 m_e$. 中文

In view of the recent results of experiments on delayed coincidences, referred to previously^{12,13}, such results must, for the present, be accepted with great reserve. We must expect the liberation of an amount of energy of magnitude 100 MeV. in any nucleus to lead to the ejection of several particles, some of which may be neutrons.

There is therefore no firm basis for assuming that the disintegration represented in Fig. 4 corresponds to the disintegration of a nucleus of nitrogen rather than one of silver or bromine. Indeed, the delayed coincidence experiments suggest that the second assumption is the more probable. When a sufficient number of observations with loaded plates has been accumulated, it may be possible to draw more definite conclusions from observed regularities in the modes of disintegration of particular types of nuclei. 中文

A detailed account of the experiments will be published elsewhere.
中文

(159, 694-697; 1947)

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References:

1. Perkins, D. H., *Nature*, **159**, 126 (1947).
2. Occhialini and Powell, *Nature*, **159**, 186 (1947).
3. Bose and Choudhuri, *Nature*, **148**, 259 (1941); **149**, 302 (1942).
4. Lattes, Fowler and Cier, *Nature*, **159**, 301 (1947).
5. Hughes, *Phys. Rev.*, **69**, 371 (1946).
6. Leprince-Ringuet and L'Héritier, *J. Phys. et Rad.*, **7**, 65 (1946).
7. Bethe, *Phys. Rev.*, **70**, 821 (1947).
8. Schwinger, *Phys. Rev.*, **61**, 387 (1942).
9. Wentzel, *Rev. Mod. Phys.*, **19**, 4 (1947).
10. Fermi, Teller and Weisskopf, *Phys. Rev.*, **71**, 314 (1947).
11. Wheeler, *Phys. Rev.*, **71**, 320 (1947).
12. Conversi, Pancini and Piccioni, *Phys. Rev.*, **71**, 209 (1947).
13. Sigurgeirsson and Yamakawa, *Phys. Rev.*, **71**, 319 (1947).
14. Zhdanov, *Akad. Nauk. Otdel. Bull. Ser. Phys.*, **3**, 734 (1938); **4**, 272 (1939). *C.R. (U.S.S.R.)*, **28**, 110 (1940).
15. Rochester, Butler and Runcorn, *Nature*, **159**, 227 (1947).

涉及带电介子的过程

拉特斯等

布里斯托尔大学的塞萨尔·拉特斯及其同事们在这篇文章中报告说，近期宇宙射线的实验结果表明存在迄今未知的粒子。他们发现一些质量比质子小的粒子可以引起核嬗变，并且在此过程中会发射出一些重粒子，他们称其为介子。介子这一专有名词是指任意一个质量介于电子和质子之间的粒子，这已得到公认。拉特斯及其同事们在照相底片上不寻常的粒子径迹中观测到了介子，同时这些照相底片还显示出这些介子有时会衰变为次级介子。随后人们将初级介子确定为正负 π 介子，几年后在实验室中生成了这些粒子。 [英文](#)

近期，我们利用照相法进行的研究^[1,2]显示，作为高纬度处宇宙辐射的组分，小质量的带电慢粒子可以进入核并引起核嬗变同时发射出重粒子。对于任何质量介于质子和电子之间的粒子，用“介子”一词来表示都是合适的。通过连续的实验我们发现了有关介子的实验证据，它们在射程末端产生了次级介子。与此同时，我们还观测到了嬗变的核发射出慢介子的嬗变过程。这些过程的某些特性虽然还有待阐明，但是由于其实验结果似乎与发展一套令人满意的核力介子理论这样的重大问题有密切关系，我们将介绍以下的实验内容。 [英文](#)

在鉴别介子的径迹时我们应用了颗粒计数法。假设一种粒子的电荷量为 $|e|$ ，如果我们的假设是正确的，那么当该粒子的射程末端终止于乳胶内时，颗粒计数法从原理上^[3]允许我们测定该粒子的质量。我们定义径迹的“颗粒密度”为单位径迹长度中的颗粒数。知道了对于乳胶的射程-能量曲线^[4]，我们就可以观测快质子的径迹，以测定描述径迹的颗粒密度与粒子能量损失率间关系的标定曲线。利用这条曲线，所观测到的沿着介子径迹的颗粒分布能够使我们推导出乳胶中粒子的总能量损失。利

用粒子被带走的能量以及观测到的粒子射程可以对粒子的质量进行测量。 [英文](#)

在测试实验中，对受粒子辐射后立即显影的照片进行观测，并用上述方法对质子质量进行测定，我们发现上述方法给出了令人满意的结果。各条径迹颗粒计数观测值的误差，只是略大于一条径迹中有限的颗粒数的统计波动对应的误差。然而，正如我们先前所强调的那样，在将这种方法用于被宇宙射线^[2]辐射数周的照片时，会产生严重的误差。这些误差主要是由于在粒子穿过照片和照片显影之间的这段时间内发生的潜影衰退。 [英文](#)

通过随机地选取来自“星”状的质子，对若干条质子径迹进行颗粒计数，来测定每张照片的标定曲线，我们试图以此顾及潜影衰退。这样一个标定曲线对应于照片中径迹衰退的一个平均值。于是，我们得到改进后同类粒子质量的平均值，对标定曲线的测定中没有用到的那些质子的径迹进行的测试性测量显示，单条径迹的颗粒计数测量值变化很大。不过，根据小角度散射的发生频率而判定其为质子的粒子，由其颗粒计数确定的粒子质量都不会超过 $2,400 m_e$ 或小于 $1,300 m_e$ 。 [英文](#)

在这些情况下，不可能太认真地相信由颗粒计数测定的单个介子质量；因为在目前的实验中我们采用这种方法，仅是为了把介子与质子的径迹区分开来。在观察一张照片时，如果乳胶中粒子的射程超过100微米，有经验的观测者通过观察很快就能学会识别出介子的径迹。然而，只有在颗粒密度和库仑散射的发生频率都与小质量粒子的特征值相对应的情形下，我们才确定这一特别的径迹是由介子产生的。尽管采取了上述的防范措施，我们仍然考虑了由于罕见的综合环境条件而将质子径迹误认为是质量小于 $400 m_e$ 的介子径迹的可能性。虽然很难给出发生这类误差的概率估计值，但我们相信这个数值是很小的。 [英文](#)

次级介子

现在，我们已经对65个介子（射程末端落在乳胶之内）的径迹做了分析，其中40个介子没有产生次级粒子的迹象。剩余的25个介子则产生了次级粒子，其中的15个介子发生嬗变并放射出两个或更多个重粒子，

我们观测到剩余的10个介子中每个介子都产生一个单独的次级粒子。而在后面提到的10个事例当中，经我们研究发现其中有4个事例的次级粒子是氢或是更重的核；另4个事例产生的次级粒子的种类还不能确定，最后2个事例产生的则是次级介子。 [英文](#)

图1是显微相片中的图像的再现，显示了粒子 m_1 在乳胶中到达了射程的末端。由靠近射程末端处散射点的频繁出现和颗粒密度的快速变化，我们推算出该径迹是由介子产生的。如图1所示，一个次级粒子 m_2 的径迹起始于第一个粒子 m_1 的终点，并且它的径迹也具有小质量粒子径迹的所有特征。图2显示了一个类似的事例。在这两张图的情形中，我们所观测到的图像是由两个不相关的事例产生的两条径迹造成的偶然毗邻的可能性不到十亿分之一。 [英文](#)

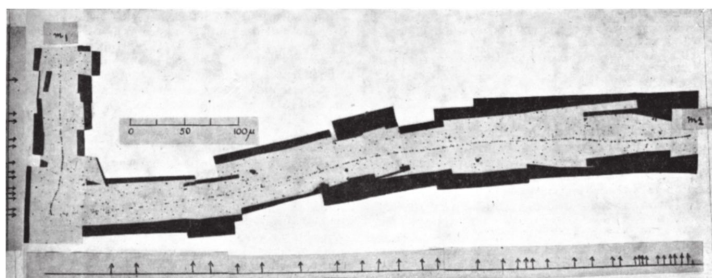


图1．由罗伯茨夫人观测。用库克45倍“萤石”物镜得到的显微照片。伊尔福载硼C2“核”乳胶。 m_1 是初级介子， m_2 是次级介子。这张和以下各张照片中的箭头，指示出显微镜观测下方向变化大于 2° 的点，所有的相片全部未经修改。 [英文](#)

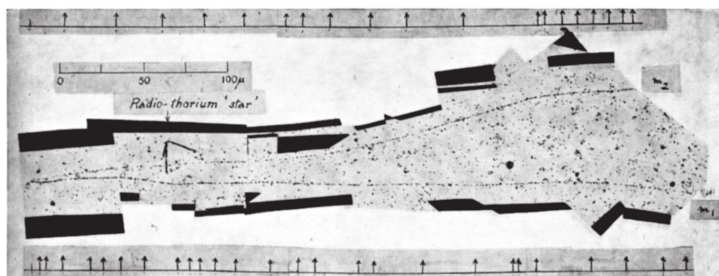


图2．由库尔茨小姐观测。库克45倍“萤石”物镜。伊尔福载硼C2“核”乳胶。次级介子 m_2 射离了乳胶。 [英文](#)

颗粒计数表明，图1和图2中初始粒子的质量分别为 $350 \pm 80 \ m_e$ 和 $330 \pm 50 \ m_e$ ；图1中次级粒子的质量为 $330 \pm 50 \ m_e$ ，误差限仅相应于与不同径迹中有限数量的颗粒关联的标准偏差。所有这些值都是从照片中衰退的平均值所对应的标定曲线导出的，如果径迹在照射后期产生，该

数值将偏高；而如果该径迹在照射早期产生，此数值就会太低。然而，我们可以假定，每个事例中的双组元径迹是迅速接连产生的，因此衰退程度相同。在这类情况下，测量表明，如果初级介子与次级介子之间存在质量差，其量级不可能大于 $100\ m_e$ 。图2提供的证据并不充分，因为次级粒子穿出了乳胶，但径迹颗粒密度的变化表明，它接近射程末端。由此我们得出结论，次级介子是以几乎相等的能量发射的。 [英文](#)

我们试图用初级介子与乳胶中的核相互作用来解释这两个事例，由这种相互作用导致了一个与初级介子质量相同的次级介子的发射。方程（1）表示的任何类型的反应都涉及能量的吸收，

$$A_Z^Y + \mu_{-1}^0 \rightarrow B_{Z-2}^Y + \mu_{+1}^0 \text{ 或者 } A_Z^Y + \mu_{+1}^0 \rightarrow C_{Z+2}^Y + \mu_{-1}^0 \quad (1)$$

式中A表示乳胶中存在的已知的任何稳定核，但这与观测到的次级介子的能量约为2兆电子伏的事实相矛盾。 [英文](#)

第二个过程用以下方程表示

$$Ag_7 + \mu_{-1}^0 \rightarrow X_Z + Y_{43-Z} + \mu_{+1}^0 \quad (2)$$

式中X和Y表示电荷数近似相等的两个核，这个反应按能量守恒可能发生，但在两个反冲核的总能量仅为几百万电子伏特量级的条件下发生的可能性很小。因此我们的照片显示的可能是不同质量的介子^[5,6,7]的存在。由颗粒计数提供的证据与这个猜想不矛盾。除了知道在乳胶中到达射程末端的一个次级介子并不引发伴随重粒子发射的嬗变外，我们还没有两个介子带电荷符号的直接证据。然而，如果我们假设，嬗变对应于初级介子与轻核的相互作用用方程（3）表示，

$$C_6^{12} + \mu_{-1}^0 \rightarrow Be_4^{12} + \mu_{+1}^0 \quad (3)$$

那么，根据对铍核的质量估计，2个介子的质量差一定是 $60\ m_e$ 的量级。

[英文](#)

我们所知道的，认为存在不同质量介子的唯一介子理论是施温格模型^[8]。该模型设想^[9]一个负矢量介子应具有很短的寿命，并应产生具有相同电荷但质量较小的赝标量介子，同时伴随量子辐射。因此，在我们

已观测的嬗变类型中测定次级介子是否总释放相同的能量将具有很大意义。如果事实果真如此，我们必定认为，我们正在处理一个比公式（3）所表示的含有特殊核的过程更为基本的过程。作为这类过程的一个例子，如果我们假定在我们实验中出现的次级介子与发射的光子的动量大小相等而方向相反，则在嬗变中释放的总能量是25兆电子伏的量级。

[英文](#)

在最近的报道中^[10,11]，从对正负介子与轻核和重核的相互作用^[12,13]产生的延迟符合的观测结果中已得出基本性结论。该结论认为，一个负介子在其射程终端落入了核的K轨道中。在重核情况下，负介子会被俘获而导致嬗变及发射重粒子。另一方面，在轻核情况下，负介子被认为在被俘获前先发生 β 衰变，因此像一个正介子一样，可以产生一个延迟符合。由此得出的结论如下，核力要比到目前为止认为的数值小几个数量级。鉴于我们的观测表明了介子衰变的一种新模式，其可能有助于解决这些困难。

[英文](#)

由核发射的介子

图3显示了一次嬗变的显微照相图像，其中可以分辨出从同一中心辐射出的6条径迹。图像边缘的字母表示特定的径迹是否穿透乳胶表面s，进入玻璃g，或终止于乳胶e中。径迹a和c的颗粒密度表明，嬗变的发生与照片显影之间的时间间隔足够短，可以避免严重的潜影衰退。

[英文](#)

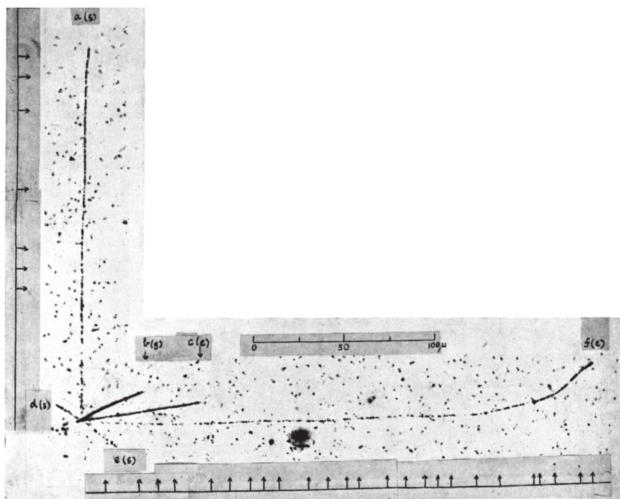


图3. 由罗伯茨夫人观测。库克45倍的“萤石”物镜下的显微相片。伊尔福载硼C2“核”乳胶。径迹 (b) 陡峭地下沉，其表观颗粒密度大于用透视缩小法得到的真值。(b) 和 (c) 可能都是由 α 粒子产生的。 [英文](#)

标记的径迹由于散射而频繁地改变方向，并且在沿着径迹的运动中，颗粒密度也快速变化。这两个特性一起确定了径迹是由轻粒子产生的，颗粒计数给出的质量估计值是 $375 \pm 70 m_e$ ^[14]。 [英文](#)

我们现在已观测到总共1,600个“星”状嬗变，每一个都会从一个核中发射出3个或更多的带电粒子。其中的170个能量释放大于或等于图4表示的“星”状嬗变中的能量释放，但仅在两个嬗变事例中我们可以判定发射粒子是介子。然而，我们并不能认为，这类嬗变中的介子发射是如这些图中所示的如此罕见。如果发射介子的能量大于5兆电子伏，在我们的实验条件下似乎很难观测到它。帝国理工学院的珀金斯先生已指出，在 B_1 乳胶中，当能量大于2兆电子伏时介子径迹的颗粒密度变得很小，在 C_2 乳胶中更高的能量下我们可以预测到类似的结果。因此，我们的观测与以下观点不矛盾：介子的发射是高能初级粒子核嬗变的共同特性；而目前的事例即粒子的发射速度特别低以至于能够鉴别粒子的种类，是一个罕有的例子。最近描述的介子产生的例子^[15]是高能初级粒子由类似过程产生的，其中，由于事例发生时铅片的深度，没有观测到嬗变中发射的一些重质量碎片。 [英文](#)

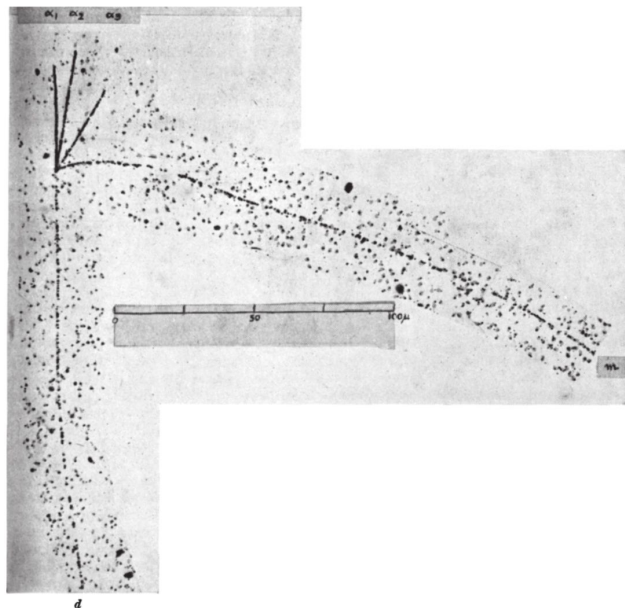


图4 . 由罗伯茨夫人观测。库克95倍消色差物镜。伊尔福载锂C2“核”乳胶。 英文

图3所示的衰变可能是高能粒子在高层大气中一类具有代表性的常见过程。在当前的例子中，初级粒子的能量至少已达到200兆电子伏，如果其质量小于或等于质子的质量，将不会在乳胶中被记录到。 英文

介子导致的嬗变

基于对嬗变中释放的总能量的观测，通过对带电介子导致的核嬗变的观测，我们提出了测定这些粒子质量的方法^[1,2]。尝试采用这个方法时，在鉴别嬗变核的种类和考虑不能被乳胶记录的发射中子问题上我们遇到了困难。图4所示的这类嬗变的一张照片初看起来似乎允许我们做出确定的结论。在照片中，我们可以分辨出四个重粒子的径迹，其中的短径迹 α_1 、 α_2 和 α_3 终止于乳胶中； α_1 和 α_2 无疑是由 α 粒子产生的，颗粒计数表明， α_3 是由质子产生的。因此，观测与以下方程一致



或者与发射若干短程粒子加上一个氦核或氘核的类似方程一致，但是后者的可能性较小。 英文

穿透乳胶的长程粒子径迹 d 的颗粒计数表明，如果它是由质子产生的，那么粒子的初始能量约为15兆电子伏。如果粒子是氘，那么其能量为30兆电子伏；或者，如果是氚核，则能量为45兆电子伏。无论如何，在嬗变中如果动量守恒，我们可以确定来自发射的中子的最小能量。结果，我们发现初级介子质量的最小值为 $240 m_e$ 。颗粒计数测定的值也是 $240 \pm 50 m_e$ 。 [英文](#)

鉴于最近的关于延迟符合的实验结果，并参考以前的结果^[12,13]，目前而言，必须以相当保留的态度采纳上述结论。我们可以预测，在任何核中释放出100兆电子伏量级的能量将导致若干个粒子的发射，其中有些可能是中子。因此，认为图4中所示的衰变是氮核嬗变而不是银或溴的嬗变的假设并没有牢固的依据。实际上，延迟符合的实验表明第二种假设具有更大的可能性。当用乳胶片积累足够数量的观测时，可能会从各类核嬗变中观测到的规律中得出更明确的结论。 [英文](#)

实验的详细情况即将在别处发表。 [英文](#)

(沈乃澍 翻译；朱永生 审稿)

A Floating Magnet

V. Arkadiev

Russian physicist V. Arkadiev here reports his observation of a levitation phenomenon achieved with the aid of a superconductor. He notes that a diamagnetic substance (in essence, a conventionally “non-magnetic” one) pulled toward a magnetic surface by gravity can hover over it. For example, a linear magnet one centimetre long could hover about one centimetre above a copper sphere some 20 metres in diameter. To prevent a magnet falling onto a diamagnetic sphere the size of the Earth, however, requires a superconductor beneath the magnet. Arkadiev demonstrates the effect with a small magnet hovering over a concave lead disk held over liquid helium. Today, with liquid nitrogen and high-temperature superconductors, Arkadiev’s levitation is a common trick in the physics classroom. [中文](#)

BY assuming that diamagnetic bodies are pushed out of a magnetic field, it may be shown that a diamagnetic particle attracted to a magnet by gravitational forces will take up a position in space in the equatorial plane of the straight magnet at a certain distance from the latter. The “satellite” can vibrate elastically about the point of equilibrium, describing a certain curve. The period of vibration in the radial and meridional directions is close to the period of the Kepler rotation of a magnetically indifferent satellite about a body of the same mass. Several identical particles arrange themselves around the

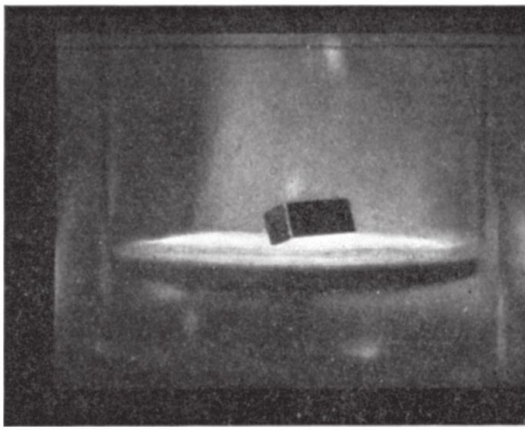
magnet. Such a combination of bodies is in the nature of a static planetary system as distinct from the Kepler dynamic planetary system. [中文](#)

However, systems thus formed can only be of small dimensions. The orbit of the outermost bodies can be no larger than several metres, and in the case of small magnetized iron meteorites amounts to several millimetres. [中文](#)

Computation shows that in space a straight magnet keeps at a certain distance from a large diamagnetic body. Thus a magnet 1 cm. long will take up a position at a distance of 1 cm. from the surface of a copper sphere about 20 m. in diameter. Diameters of 300 m. and 3,000 m. respectively would be necessary for bismuth and carbon spheres. To prevent a magnet falling on to a diamagnetic sphere the size of the Earth, the sphere must consist of the strongest diamagnetic substance, or be a superconductor. In this case, however, it is sufficient that the superconductor is placed only under the magnet itself. [中文](#)

The approach of a magnet to the surface of a superconductive semispace is accompanied by the appearance of the magnetic image of this magnet within the superconductor. In the case of a common steel magnet, this may lead to demagnetization, while a ferro-nickel-aluminium steel magnet will be repelled from the horizontal surface of the semispace with such force that it will hang suspended ("float") over the latter without any support. Thus one of the cases of a static planetary system may be reproduced in the laboratory. The Earth, screened by a superconductor in the neighbourhood of a magnet, repels the latter with the same force as it is attracted owing to universal gravitation. The accompanying photograph shows a magnet, 4 mm. $\times$ 4 mm. $\times$ 10 mm. in dimensions, floating above a concave lead disk 40 mm. in diameter in a Dewar vessel over liquid helium.

[中文](#)



中文

The experimental test of these views was possible through the kindness of Prof. P. L. Kapitza, in the Institute of Physical Problems, Moscow. 中文

The lower the coercive force of the magnet, the smaller the magnet itself must be. Carbon steel magnets, for example, can “float” when they have the dimensions of 0.5 mm. $\times$ 9 mm. By scattering microscopically small magnets over the surface of a body, it is possible to reveal superconductive inclusions directly, since the magnetic particles will roll to the spots where there is no superconductivity.

中文

(160, 330; 1947)

V. Arkadiev: Maxwell Laboratory, Physical Department, University, Moscow, March 25.

悬浮的磁体

阿卡迪耶夫

俄罗斯物理学家阿卡迪耶夫在本文中报道了他借助超导体对悬浮现象所做的观察。他注意到，在重力的作用下被拉向磁体表面的抗磁物质（其实就是传统的“非磁性”物质）可以停留在其上方。譬如说，一个1厘米长的条状磁体可以飘浮在直径约为20米的铜球上方约1厘米处。然而，为了避免磁体落到具有地球尺寸大小的抗磁性球体上，需要在磁体下方放置一个超导体。阿卡迪耶夫通过一个在置于液氮中的凹面铅盘上方悬浮的小磁体来演示上述效应。如今，利用液氮和高温超导体技术，阿卡迪耶夫悬浮已成为物理课堂中一个常用的演示。 [英文](#)

假设磁场排斥抗磁体，我们也许可以看到，当抗磁粒子因为重力作用而落向磁体时，其将会处于条形磁体中心面所在空间的某个位置上，与条形磁体相距一定距离。通常这个“卫星”可以围绕平衡点作弹性振动，得到某一曲线轨迹。而径向和经向的振动周期接近于与磁性无关的卫星围绕具有相同质量的物体作开普勒转动的周期。若有几个这样的粒子则会围绕磁体取一定的排列。这种物体的组合在性质上是静态行星系，与开普勒动力学的行星系有所不同。 [英文](#)

然而，由此形成的系统只能是小尺寸的。最远物体的轨道可能不会大于几米，对于小块磁化了的铁陨石，其量级仅为几毫米。 [英文](#)

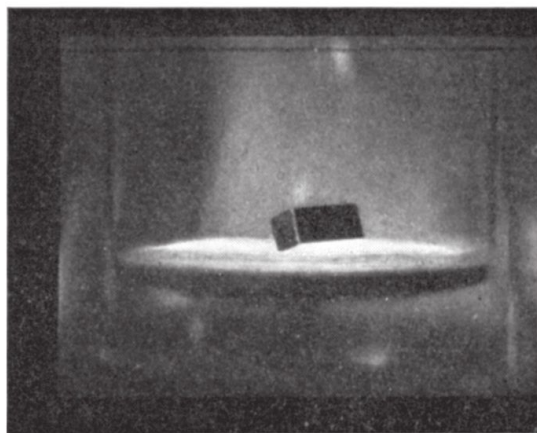
计算表明，条形磁体与大块抗磁体间可在空间中保持一定的距离。因此1厘米长的磁体将与直径约为20米的铜球表面保持1厘米的距离。而对铋球和碳球而言，则其直径分别需要达到300米和3,000米才能实现上述距离。为了防止磁体落到具有地球尺寸大小的抗磁球体上，该球体必须由最强的抗磁物质组成，或是一个超导体。然而，在这种情况下，只

要在磁体下方放置一个超导体就能实现上述情况。

英文

磁体靠近超导半空间表面时在超导体内部产生该磁体的映像。对一个普通的钢磁体而言，这将导致退磁；而对一个含有铁-镍-铝的钢磁体，在这种力的作用下将被排斥在超导半空间的水平面以外，即使没有支撑物也能悬浮（“漂浮”）在该水平面上方。因此，一种静态行星系中的情况可能在实验室中重现。但被与磁体相邻的超导体所屏蔽的地球，将以与万有引力相同大小的力把磁体推开。附图的照片展示了尺寸为4毫米×4毫米×10毫米的磁体，悬浮在充有液氮的杜瓦瓶内直径为40毫米的凹面铅盘的上方。

英文



英文

在莫斯科物理问题研究所卡皮查教授的热心帮助下，检验这些观点的实验才得以顺利开展。

英文

磁体的抗磁力越低，则磁体本身必然越小。例如，碳钢磁体在其尺寸小至0.5毫米×9毫米时才可能“浮起”。将微观尺度中的小磁体散在物体表面上，就有可能直接揭示出超导杂质的存在，因为磁性粒子将会滚到没有超导电性的地方。

英文

（沈乃澂 翻译；赵见高 审稿）

Observations on the Tracks of Slow Mesons in Photographic Emulsions*

C. M. G. Lattes *et al.*

Physicists in the late 1940s had adopted the term “meson” to refer to any particle having mass between that of an electron and a proton. Here the Brazilian physicist Cesar Lattes and colleagues reported on their observations of several hundred meson-like particles detected in photographic plates exposed at high altitudes, and presumably having origins as cosmic rays. Their observations led them to suggest that some of the initial mesons, when striking the photographic emulsions, created secondary mesons of a new kind. It soon became clear that this new particle—the pion—takes part in nuclear interactions. It was initially predicted to mediate such interactions by Hideki Yukawa in 1935, a prediction for which he won the Nobel Prize in 1949. [中文](#)

INTRODUCTION. In recent experiments, it has been shown that charged mesons, brought to rest in photographic emulsions, sometimes lead to the production of secondary mesons. We have now extended these observations by examining plates exposed in the Bolivian Andes at a height of 5,500 m., and have found, in all, forty examples of the process leading to the production of secondary mesons. In eleven of these, the secondary particle is brought to rest in

the emulsion so that its range can be determined. In Part 1 of this article, the measurements made on these tracks are described, and it is shown that they provide evidence for the existence of mesons of different mass; In Part 2, we present further evidence on the production of mesons, which allows us to show that many of the observed mesons are locally generated in the “explosive” disintegration of nuclei, and to discuss the relationship of the different types of mesons observed in photographic plates to the penetrating component of the cosmic radiation investigated in experiments with Wilson chambers and counters. [中文](#)

Part 1. Existence of Mesons of Different Mass

As in the previous communications¹, we refer to any particle with a mass intermediate between that of a proton and an electron as a meson. It may be emphasized that, in using this term, we do not imply that the corresponding particle necessarily has a strong interaction with nucleons, or that it is closely associated with the forces responsible for the cohesion of nuclei. [中文](#)

We have now observed a total of 644 meson tracks which end in the emulsion of our plates. 451 of these were found, in plates of various types, exposed at an altitude of 2,800 m. at the Observatory of the Pic du Midi, in the Pyrenees; and 193 in similar plates exposed at 5,500 m. at Chacaltaya in the Bolivian Andes. The 451 tracks in the plates exposed at an altitude of 2,800 m. were observed in the examination of 5 c.c. emulsion. This corresponds to the arrival of about 1.5 mesons per c.c. per day, a figure which represents a lower limit, for the tracks of some mesons may be lost through fading, and through failure to observe tracks of very short range. The true number will thus be somewhat higher. In any event, the value is of the same order of magnitude as that we should expect to observe in delayed coincidence experiments at a height of 2,800 m., basing our estimates on the observations obtained in similar experiments at sea-level, and making

reasonable assumptions about the increase in the number of slow mesons with altitude. It is therefore certain that the mesons we observe are a common constituent of the cosmic radiation. 中文

Photomicrographs of two of the new examples of secondary mesons, Nos. III and IV, are shown in Figs. 1 and 2. Table 1 gives details of the characteristics of all events of this type observed up to the time of writing, in which the secondary particle comes to the end of its range in the emulsion. 中文

Table 1

Event No.	Range in emulsion in microns of Primary meson	Range in emulsion in microns of Secondary meson
I	133	613
II	84	565
III	1,040	621
IV	133	591
V	117	638
VI	49	595
VII	460	616
VIII	900	610
IX	239	666
X	256	637
XI	81	590

Mean range $614 \pm 8 \mu$. Straggling coefficient $\sqrt{\Sigma \Delta_i^2/n} = 4.3$ percent, where $\Delta_i = R_i - \bar{R}$, R_i being the range of a secondary meson, and $\bar{R}$ the mean value for n particles of this type. 中文

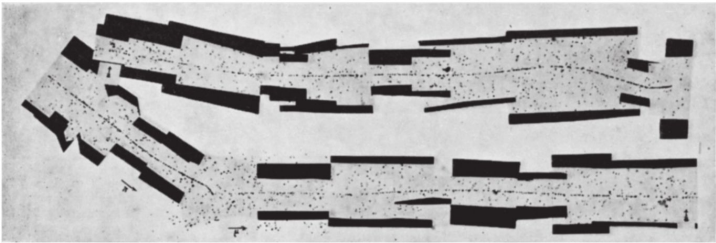


Fig. 1. Observation by Mrs. I. Powell. Cooke $\times 95$ achromatic objective; C2 Ilford Nuclear Research emulsion loaded with boron. The track of the μ -meson is given in two parts, the point of junction being indicated by a and an arrow 中文

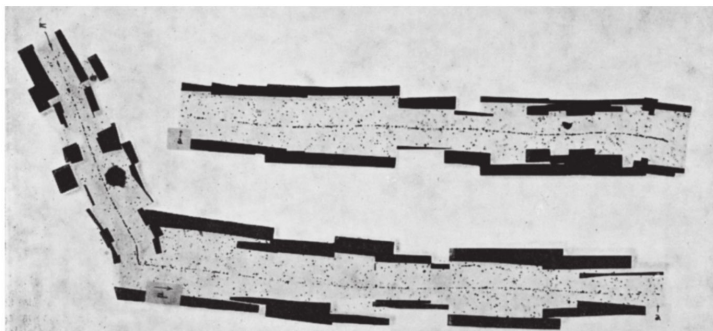


Fig. 2. Cooke $\times 95$ achromatic objective. C2 Ilford Nuclear Research emulsion loaded with boron [中文](#)

The distribution in range of the secondary particles is shown in Fig. 3. The values refer to the lengths of the projections of the actual trajectories of the particles on a plane parallel to the surface of the emulsion. The true ranges cannot, however, be very different from the values given, for each track is inclined at only a small angle to the plane of the emulsion over the greater part of its length. In addition to the results for the secondary mesons which stop in the emulsion, and which are represented in Fig. 3 by black squares, the length of a number of tracks from the same process, which pass out of the emulsion when near the end of their range, are represented by open squares.

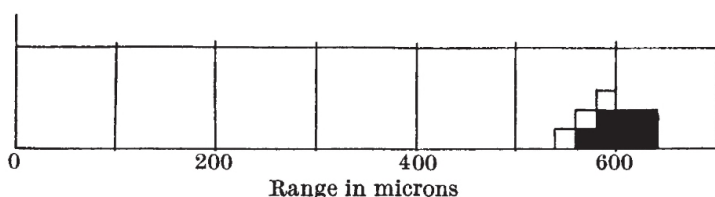


Fig. 3. Distribution in range of ten secondary mesons. Those marked $\blacksquare$ stop in the emulsion; the three marked $\square$ leave the emulsion when near the end of their range. Mean range of secondary mesons, 606 microns. The results for events Nos.VIII to XI are not included in the figure [中文](#)

The μ -Decay of Mesons

Two important conclusions follow from these measurements. Our observations show that the directions of ejection of the secondary

mesons are orientated at random. We can therefore calculate the probability that the trajectory of a secondary meson, produced in a process of the type which we observe, will remain within the emulsion, of thickness $50\ \mu$, for a distance greater than $500\ \mu$. If we assume, as a first approximation, that the trajectories are rectilinear, we obtain a value for the probability of 1 in 20. The marked Coulomb scattering of mesons in the Nuclear Research emulsions will, in fact, increase the probability of “escape”. The six events which we observe in plates exposed at 2,800 m., in which the secondary particle remains in the emulsion for a distance greater than $500\ \mu$, therefore correspond to the occurrence in the emulsion of 120 ± 50 events of this particular type. Our observations, therefore, prove that the production of a secondary meson is a common mode of decay of a considerable fraction of those mesons which come to the end of their range in the emulsion. 中文

Second, there is remarkable consistency between the values of the range of the secondary mesons, the variation among the individual values being similar to that to be expected from “straggling”, if the particles are always ejected with the same velocity. We can therefore conclude that the secondary mesons are all of the same mass and that they are emitted with constant kinetic energy. 中文

If mesons of lower range are sometimes emitted in an alternative type of process, they must occur much less frequently than those which we have observed; for the geometrical conditions, and the greater average grain-density in the tracks, would provide much more favourable conditions for their detection. In fact, we have found no such mesons of shorter range. We cannot, however, be certain that mesons of greater range are not sometimes produced. Both the lower ionization in the beginning of the trajectory, and the even more unfavourable conditions of detection associated with the greater lengths of the tracks, would make such a group, or groups, difficult to observe.

Because of the large fraction of the mesons which, as we have seen, can be attributed to the observed process, it is reasonable to assume that alternative modes of decay, if they exist, are much less frequent than that which we have observed. There is, therefore, good evidence for the production of a single homogeneous group of secondary mesons, constant in mass and kinetic energy. This strongly suggests a fundamental process, and not one involving an interaction of a primary meson with a particular type of nucleus in the emulsion. It is convenient to refer to this process in what follows as the μ -decay. We represent the primary mesons by the symbol π , and the secondary by μ . Up to the present, we have no evidence from which to deduce the sign of the electric charge of these particles. In every case in which they have been observed to come to the end of their range in the emulsion, the particles appear to stop without entering nuclei to produce disintegrations with the emission of heavy particles. 中文

Knowing the range-energy relation for protons in the emulsion, the energy of ejection of the secondary mesons can be deduced from their observed range, if a value of the mass of the particles is assumed. The values thus calculated for various masses are shown in Table 2. 中文

Table 2

Mass in m_e	100	150	200	250	300
Energy in MeV.	3.0	3.6	4.1	4.5	4.85

No established range-energy relation is available for protons of energies above 13 MeV., and it has therefore been necessary to rely on an extrapolation of the relation established for low energies. We estimate that the energies given in Table 2 are correct to within 10 percent. 中文

Evidence of a Difference in Mass of π - and μ -Mesons

It has been pointed out¹ that it is difficult to account for the μ -decay

in terms of an interaction of the primary meson with the nucleus of an atom in the emulsion leading to the production of an energetic meson of the same mass as the first. It was therefore suggested that the observations indicate the existence of mesons of different mass. Since the argument in support of this view relied entirely on the principle of the conservation of energy, a search was made for processes which were capable of yielding the necessary release of energy, irrespective of their plausibility on other grounds. Dr. F. C. Frank has re-examined such possibilities in much more detail, and his conclusions are given in an article to follow. His analysis shows that it is very difficult to account for our observations, either in terms of a nuclear disintegration, or of a “building-up” process in which, through an assumed combination of a negative meson with a hydrogen nucleus, protons are enabled to enter stable nuclei of the light elements with the release of binding energy. We have now found it possible to reinforce this general argument for the existence of mesons of different mass with evidence based on grain-counts. [中文](#)

We have emphasized repeatedly¹ that it is necessary to observe great caution in drawing conclusions about the mass of particles from grain-counts. The main source of error in such determinations arises from the fugitive nature of the latent image produced in the silver halide granules by the passage of fast particles. In the case of the μ -decay process, however, an important simplification occurs. It is reasonable to assume that the two meson tracks are formed in quick succession, and are subject to the same degree of fading. Secondly, the complete double track in such an event is contained in a very small volume of the emulsion, and the processing conditions are therefore identical for both tracks, apart from the variation of the degree of development with depth. These features ensure that we are provided with very favourable conditions in which to determine the ratio of the masses of the π - and μ -mesons, in some of these events. [中文](#)

In determining the grain density in a track, we count the number of individual grains in successive intervals of length $50\ \mu$ along the trajectory, the observation being made with optical equipment giving large magnification ($\times 2,000$), and the highest available resolving power. Typical results for protons and mesons are shown in Fig. 4. These results were obtained from observations on the tracks in a single plate, and it will be seen that there is satisfactory resolution between the curves for particles of different types. The “spread” in the results for different particles of the same type can be attributed to the different degrees of fading associated with the different times of passage of the particles through the emulsion during an exposure of six weeks. 中文

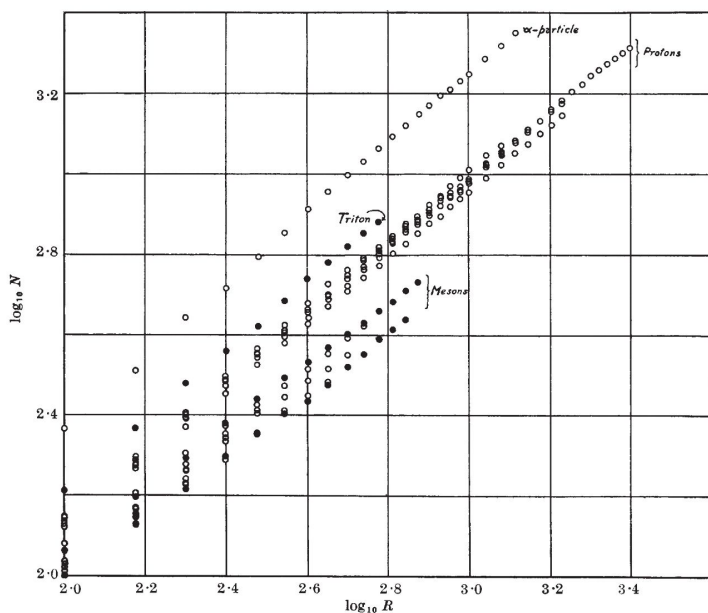


Fig. 4. N is total number of grains in track of residual range R (scale-divisions). 1 scale-division = $0.85\ \mu$ 中文

Applying these methods to the examples of the μ -decay process, in which the secondary mesons come to the end of their range in the emulsion, it is found that in every case the line representing the observations on the primary meson lies above that for the secondary particle. We can therefore conclude that there is a significant

difference in the grain-density in the tracks of the primary and secondary mesons, and therefore a difference in the mass of the particles. This conclusion depends, of course, on the assumption that the π^- - and μ^- -particles carry equal charges. The grain-density at the ends of the tracks, of particles of both types, are consistent with the view that the charges are of magnitude $|e|$. [中文](#)

A more precise comparison of the masses of the π^- - and μ^- -mesons can only be made in those cases in which the length of the track of the primary meson in the emulsion is of the order of 600 μ . The probability of such a favourable event is rather small, and the only examples we have hitherto observed are those listed as Nos. III and VIII in Table 1. A mosaic of micrographs of a part only of the first of these events is reproduced in Fig. 1, for the length of the track of the μ^- -meson in the emulsion exceeds 1,000 μ . The logarithms of the numbers of grains in the tracks of the primary and secondary mesons in this event are plotted against the logarithm of the residual range in Fig. 5. By comparing the residual ranges at which the grain-densities in the two tracks have the same value, we can deduce the ratio of the masses. We thus obtain the result $m_{\pi^-}/m_{\mu^-}=2.0$. Similar measurements on event No. VIII give the value 1.8. In considering the significance which can be attached to this result, it must be noticed that in addition to the standard deviations in the number of grains counted, there are other possible sources of error. Difficulties arise, for example, from the fact that the emulsions do not consist of a completely uniform distribution of silver halide grains. "Islands" exist, in which the concentration of grains is significantly higher, or significantly lower, than the average values, the variations being much greater than those associated with random fluctuations. The measurements on the other examples of μ^- -decay are much less reliable on account of the restricted range of the π^- -mesons in the emulsion; but they give results lower than the above values. We think it unlikely, however, that the true ratio is as low as 1.5. [中文](#)

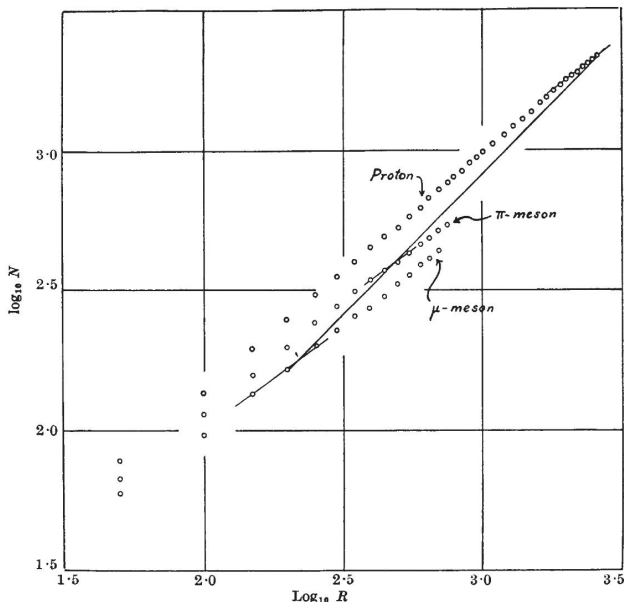


Fig. 5. N is total number of grains in track of residual range R (scale-divisions). 1 scale-division = 0.85 microns. The 45°-line cuts the curves of the mesons and proton in the region of the same grain density 中文

The above result has an important bearing on the interpretation of the μ -decay process. Let us assume that it corresponds to the spontaneous decay of the heavier π -meson, in which the momentum of the μ -meson is equal and opposite to that of an emitted photon. For any assumed value of the mass of the μ -meson, we can calculate the energy of ejection of the particle from its observed range, and thus determine its momentum. The momentum, and hence the energy of the emitted photon, is thus defined; the mass of the π -meson follows from the relation

$$c^2 m_{\pi} = c^2 m_{\mu} + E_{\mu} + h\nu.$$

中文

It can thus be shown that the ratio m_{π}/m_{μ} is less than 1.45 for any assumed value of m_{μ} in the range from 100 to 300 m_e , m_e being the mass of the electron (see Table 3). A similar result is obtained if it is assumed that a particle of low mass, such as an electron or a neutrino,

is ejected in the opposite direction to the μ -meson. 中文

Table 3

Assumed mass m_μ	$E(\text{McV})$	$h\nu(\text{McV})$	m_π	$m_\pi/m_\mu \pm 3$ percent
100 m	3.0	17	140 m_e	1.40
150	3.6	23	203	1.35
200	4.1	29	264	1.32
250	4.5	34	325	1.30
300	4.85	39	387	1.29

中文

On the other hand, if it is assumed that the momentum balance in the μ -decay is obtained by the emission of a neutral particle of mass equal to the μ -meson mass, the calculated ratio is about 2.1:1. 中文

Our preliminary measurements appear to indicate, therefore, that the emission of the secondary meson cannot be regarded as due to a spontaneous decay of the primary particle, in which the momentum balance is provided by a photon, or by a particle of small rest-mass. On the other hand, the results are consistent with the view that a neutral particle of approximately the same rest-mass as the μ -meson is emitted. A final conclusion may become possible when further examples of the μ -decay, giving favourable conditions for grain-counts, have been discovered. 中文

(160, 453-456; 1947)

C. M. G. Lattes, G. P. S. Occhialini and C. F. Powell: H. H. Wills Physical Laboratory, University of Bristol.

Reference:

- 1. *Nature*, **159**, 93, 186, 694 (1947).

* This article contains a summary of the main features of a number of lectures given, one at Manchester on June 18 and four at the Conference on Cosmic Rays and Nuclear Physics, organised by Prof. W. Heitler, at the Dublin Institute of Advanced Studies, July 5-12. A complete account of the observations, and of the conclusions which follow from them, will be published elsewhere.

感光乳胶中慢介子径迹的观测*

拉特斯等

20世纪40年代后期，物理学家采用“介子”来称谓所有质量介于电子和质子间的粒子。在这篇论文中，巴西物理学家塞萨尔·拉特斯和他的同事们报道了在高海拔处受照射的照片中探测到几百个类介子粒子的观测结果，并推测其源自宇宙射线。根据上述观测结果，他们提出，初级介子进入感光乳胶时，有一部分产生了一种新的次级介子。不久他们就弄清楚了这种新粒子（即 π 介子）参与了核相互作用。早在1935年汤川秀树首先预言了 π 介子是核作用的媒介，由此他获得了1949年的诺贝尔奖。 [英文](#)

引言 最近实验显示，终止于感光乳胶中的带电介子有时会导致次级介子的产生。我们现已通过检查置于玻利维亚安第斯山脉海拔5,500米处的受照射的底片来延伸这些观测，现已发现共计有40个导致次级介子产生的事例。其中11个事例的次级粒子终止于乳胶中，因此其射程是可以确定的。本文的第一部分描述了对这些粒子径迹的测量，同时也证明了不同质量介子的存在。第二部分中（编者注：本书未收录第二部分），我们进一步证明了介子的产生，这使得我们可以得出，许多可观测到的介子是以“爆炸”式的核嬗变在局部区域产生的，同时也使我们可以对威尔逊云室和计数器实验中研究的宇宙射线的穿透成分与受照的感光底片中观测到的不同类型介子之间的关系进行探讨。 [英文](#)

第一部分. 不同质量介子的存在

如之前的报道^[1]所述，我们把所有质量介于电子与质子之间的粒子称为介子。在这里需要强调的是，使用这个术语并不意味着我们认为相应的粒子必然与核子有强相互作用，或是与核的凝聚力密切相关。

我们现已观测到终止于底片乳胶中的介子径迹总共为644条，其中451条发现于比利牛斯山脉的米迪山峰海拔2,800米处天文台受照射的不同类型的底片中；另外193条发现于玻利维亚安第斯山脉恰卡尔塔亚山海拔5,500米处受照射的类似底片中。海拔2,800米处受照底片中的451条径迹是在5厘米³的乳胶检测中观测到的，这相当于每天每立方厘米乳胶中到达约1.5个介子。该数据是一个下限，因为某些介子的径迹可能由于潜影衰退和射程极短难以观测而丢失。因此，真正的数值将会比该数值要稍高一些。基于我们在海平面上类似实验观测的估计，以及慢介子数目随着海拔上升而增大的合理猜想，总是可以得出，这个数值与我们在2,800米高度延迟符合实验的观测中所预期的数值具有相同量级。因此可以确定，我们观测到的介子是宇宙射线的一般组分。

英文

图1和图2分别是次级介子的两个新事例III和IV的显微照片。表1给出了直至本文执笔时观测到的所有这类事例的详细特性，其中次级粒子射程末端终止于乳胶中。

英文

表1

事例编号	初级介子在乳胶中的射程	次级介子在乳胶中的射程
I	133	613
II	84	565
III	1,040	621
IV	133	591
V	117	638
VI	49	595
VII	460	616
VIII	900	610
IX	239	666
X	256	637
XI	81	590

平均射程：614±8微米。离散系数： $\sqrt{\Sigma \Delta_i^2/n} = 4.3\%$ ，式中， $\Delta_i = R_i - \bar{R}$ ， R_i 是次级介子的射程， $\bar{R}$ 是n个这类粒子的射程平均值。

英文

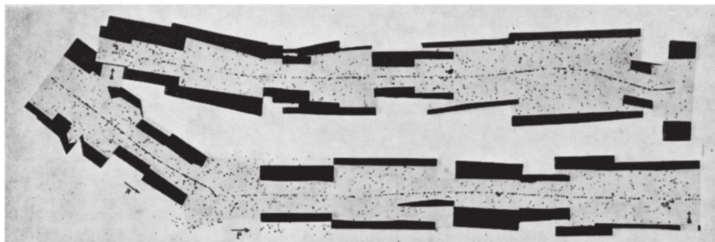


图1．由鲍威尔夫人观测。库克95倍消色差物镜；C2伊尔福载硼核乳胶。 μ 介子（编者注：现在粒子物理认为“ μ 介子”不是介子，而是一种轻子，因此正确的称谓应为“ μ 子”。考虑到历史原因，文中仍保留“ μ 介子”的译法）的径迹由两部分给出，连接点用 a 和箭头表示。 [英文](#)

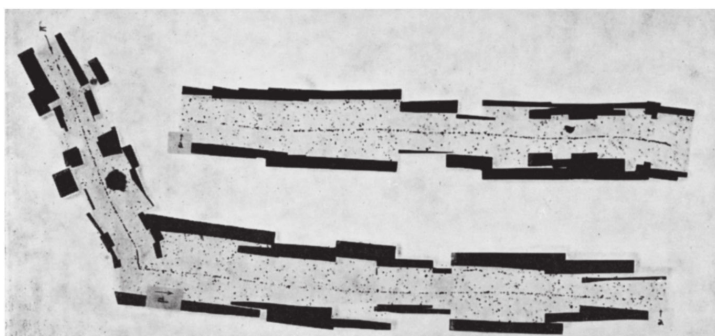


图2．库克95倍消色差物镜。C2伊尔福载硼核乳胶。 [英文](#)

图3是次级粒子射程的分布，这些值指的是粒子实际径迹在平行于乳胶表面的平面上的投影长度。不过真实的射程不会与给出的数值有很大的差异，因为每个径迹在大部分长度中相对于乳胶平面只倾斜很小的角度。图3中除了用黑方块表示出终止于乳胶中的次级粒子的结果之外，还用白方块表示出产生于相同过程的、于射程末端附近穿出乳胶的一些径迹的长度。 [英文](#)

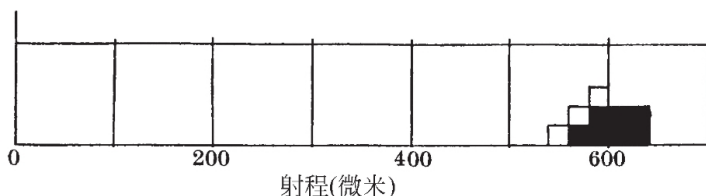


图3．10个次级介子的射程分布。■表示7个次级介子在乳胶中停止；3个□表示3个次级介子在接近射程末端时离开乳胶。次级介子的平均射程为606微米。事例VIII~XI的结果未包含在本图内。 [英文](#)

介子的 μ 衰变

从以上测量中得到了两个重要的结论。我们的观测表明，次级介子

的发射方向是随机的。因此，我们可以计算出我们所观测的那类过程中产生的次级介子径迹停留在厚度为50微米乳胶内且射程大于500微米的概率。作为一个初步近似，如果我们假定径迹是直线，则我们得出的概率为1/20。实际上，核乳胶中介子的显著的库仑散射将增加“逃逸”的概率。我们在海拔2,800米处受照底片中观测到的6个事例中的次级粒子在乳胶中的射程大于500微米，因而这6个事例相当于乳胶中出现 120 ± 50 个这类特殊形式的事例。因此我们的观测证明，对于射程终止于乳胶内的介子，相当大一部分的衰变模式通常是产生次级介子。 [英文](#)

其次，次级介子射程值之间存在显著的一致性，如果粒子总以相同的速度发射，各个数值之间的变化类似于“离散”预期的值。因此我们可以得出，次级介子是质量相同的粒子，它们会以恒定的动能发射。

[英文](#)

如果较短射程的介子偶尔以另一种类型的方式发射，它们出现的频率必定比我们观测到的要低得多；因为几何条件以及径迹中较大的平均颗粒密度将会为探测它们提供更为有利的条件。实际上，我们尚未发现这类较短程的介子。然而，我们不能肯定是否有时候会产生更长射程的介子。长程介子径迹开始处的电离能力较低，加之与长径迹相关的更不利的探测条件，这两个因素将使这一类或这些类长程介子难以观测。如我们所见，由于大部分介子产生于我们已观测到的过程，因此有理由假设，如果存在其他模式的衰变，其出现频率要远低于我们已观测到的过程。因此，有力的证据证明，只产生了质量和动能为常数的一类次级介子。这就强有力地提出了一个基本过程，但这个过程并不涉及初级粒子与乳胶中的特殊类型核的相互作用。为方便起见，这一过程在后面的陈述中被称为 μ 衰变。我们用 π 表示初级介子， μ 表示次级介子。至今，我们尚无可以推断出这些粒子的电荷符号的证据。在粒子射程末端终止于乳胶中的事例中，粒子停止时似乎并未进入核并产生发射重粒子的嬗变。 [英文](#)

知道了乳胶中质子的射程-能量关系后，如果设定了粒子的某个质量值，次级介子的发射能量便可以根据其观测到的射程导出。据此，表2列出了不同质量对应的介子能量的计算值。 [英文](#)

表2

质量 (m_e)	100	150	200	250	300
能量 (兆电子伏)	3.0	3.6	4.1	4.5	4.85

对于能量大于13兆电子伏的质子尚未确立射程-能量关系，因此必须依靠已经确立的低能关系外推。我们估计，表2中给出的能量在10%以内是正确的。 [英文](#)

π 介子和 μ 介子质量差的证据

我们已指出^[1]，用初级介子与乳胶中原子核的相互作用导致一个与初级介子质量相同的高能介子的产生难以解释 μ 衰变。因此可以认为，已有的观测表明存在不同质量的介子。由于支持这个观点的论据完全依赖于能量守恒定律，因此无论它们在其他理论背景中的合理性如何，都对能够产生必要的能量释放的若干过程进行了探索。弗兰克博士更加仔细地重新检验了这种可能性，并在随后发表的一篇论文中给出了他的结论。他的分析指出，无论用核嬗变或用“聚集”过程都很难解释我们的观测，其中“聚集”过程是指，假设负介子能够与氢核结合，质子可以进入轻元素的稳定核内并释放结合能。我们现已发现，基于颗粒计数的证据，可能会巩固存在不同质量介子的总论点。 [英文](#)

我们已反复强调^[1]，由颗粒计数推出粒子质量的结论时，一定要十分地谨慎。这类测定中的误差主要来自自由快速粒子通过卤化银颗粒所产生的潜影的易变性。然而，在 μ 衰变过程的情况下，出现了重要的简化现象。我们可以合理地假设，两个介子的径迹是快速接连产生的，并遭到相同程度的潜像衰退。其次，在这类事例中完全的双径迹包含于很小的乳胶体积内，因此除了显影的程度在深度上的变化之外，两条径迹的处理条件是一样的。这些特点保证了我们是在非常有利的条件下，利用这一类事例来测定 π 介子和 μ 介子的质量比。 [英文](#)

测定径迹的颗粒密度时，我们沿着径迹对每50微米长度间隔内的颗粒计数依次进行了统计，观测是用大放大倍数（ $\times 2,000$ ）的光学装置，并达到了最高可能的分辨率。图4是质子和介子的典型结果。这些结果是从单张底片的径迹观测中获得的，我们看到在不同类型的粒子曲线间得到了满意的分辨率。结果中相同类型的不同粒子的“发散”可归因

于，在6周的受照期间内，与粒子穿过乳胶的时间相关的不同程度的潜影衰退。 英文

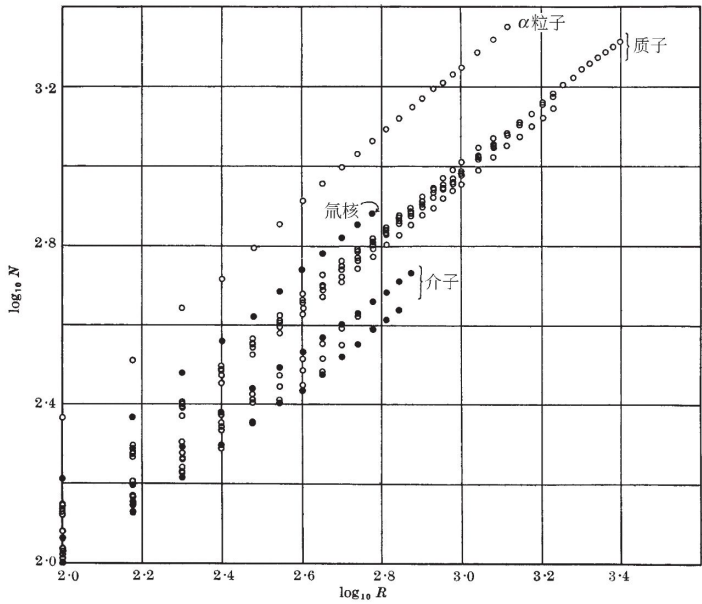


图4 . N 是剩余射程 R 径迹中的颗粒总数（标尺分度）。1标尺分度=0.85微米 英文

将这些方法应用于那些次级介子射程末端终止于乳胶内的 μ 衰变过程，我们发现，在所有这些事例中表示初级介子观测的线位于次级粒子之上。因此我们可以认为，初级介子与次级介子径迹中的颗粒密度存在显著差异，从而可知它们的质量也是不同的。当然，这个结论依赖于 π 介子和 μ 介子带有相等电荷的假定。两类粒子在径迹末端的颗粒密度与电荷量为 $|e|$ 的观点是一致的。 英文

对 μ 介子和 π 介子质量更精密的比较只能在下述情况下进行，即乳胶中初级介子的径迹长度为600微米量级的情况。这样理想的事例的出现概率是很小的，表1中的III和VIII列出了我们迄今为止观测到的仅有的例子。第一个这样事例的部分显微照片的图像重现于图1，其中乳胶中的 μ 介子径迹长度超过1,000微米。图5是这一事例中初级和次级介子径迹颗粒数的对数与剩余射程的对数的关系图。通过比较在两个径迹中具有相同颗粒密度的剩余射程，我们可以导出质量比。据此，我们获得的结果为 $m_{\pi}/m_{\mu} = 2.0$ 。对事例VIII的类似测量给出的值为1.8。在考虑这项结果的意义时必须注意到，除颗粒计数的标准偏差外，还存在其他可能的

误差来源。例如，由于乳胶不是由完全均匀分布的卤化银颗粒构成而导致的误差。其中存在一些“岛屿”，其颗粒密度明显高于或低于平均值，其变化量比随机涨落要大得多。考虑到乳胶中 π 介子的有限射程， μ 衰变的其他事例的测量不太可靠；不过它们给出的结果低于上述数值。尽管如此，我们认为真正的比值不可能低到1.5。 [英文](#)

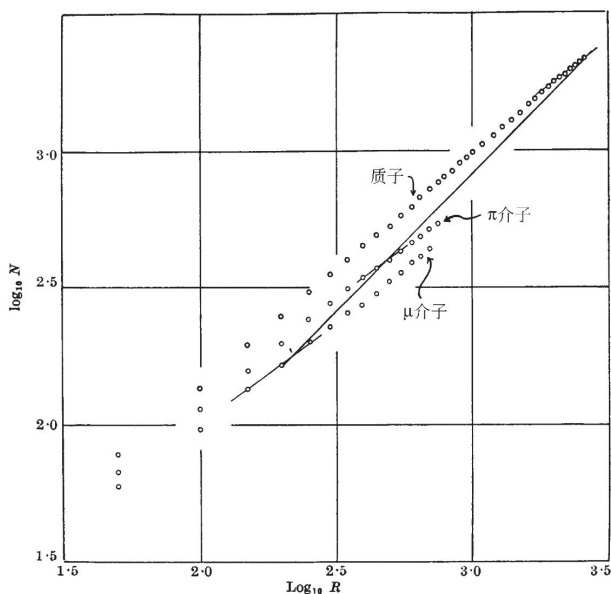


图5 . N 是剩余射程 R 的径迹中的颗粒总数（标尺分度）。1标尺分度=0.85微米。45°线在相同的颗粒密度区域处与介子和质子曲线相交。 [英文](#)

上述结果对 μ 衰变过程的解释具有重要的意义。我们假定，它相应于较重的 π 介子的自发衰变，其中 μ 介子的动量与发射光子的动量数值相等但方向相反。对 μ 介子质量的任何假定值，我们均能通过粒子的观测射程值计算其发射能量值，从而确定其动量。据此可以确定发射光子的动量和能量； π 介子的质量遵从以下关系：

$$c^2 m_{\pi} = c^2 m_{\mu} + E_{\mu} + h\nu$$

[英文](#)

因此可以表明，对质量 m_{μ} 在 $100 m_e \sim 300 m_e$ 区间内的任意假定值， m_{π}/m_{μ} 比值都小于1.45，其中 m_e 是电子质量（见表3）。如果假定一个小质量粒子，例如电子或中微子，与 μ 介子以相反方向射出，亦会得到类似结果。 [英文](#)

表3

假定质量 m_μ	E (兆电子伏)	$h\nu$ (兆电子伏)	m_π	$m_\pi/m_\mu \pm 3\%$
100 m	3.0	17	140 m_e	1.40
150	3.6	23	203	1.35
200	4.1	29	264	1.32
250	4.5	34	325	1.30
300	4.85	39	387	1.29

英文

另一方面，如果假定在 μ 衰变中的动量平衡是通过发射一个与 μ 介子质量相等的中性粒子而达到的，则计算出的比值约为2.1 : 1。 英文

因此，我们的初步测量表明，不能将次级介子的发射归因于初级粒子的自发衰变，其中一个光子或静止质量很小的粒子提供了动量平衡。另一方面，观测结果与发射了一个与 μ 介子质量近似相等的中性粒子的观点相一致。当发现了更多的能够为颗粒计数提供更有利条件的 μ 衰变事例时，才有可能做出最终的结论。 英文

(沈乃澂 翻译；朱永生 审稿)

* 这篇论文包含一些已做的演讲主要内容的总结，其中一篇是6月18日在曼彻斯特发表的，还有4篇是于7月5日~12日在都柏林高等研究所由海特勒教授组织的宇宙射线和核物理会议上发表的。关于这些观测及由此导出的结论的完整描述将在别处发表。

Evidence for the Existence of New Unstable Elementary Particles

G. D. Rochester and C. C. Butler

By 1947, physicists knew of the positron and the neutrino, and had recently discovered the neutral pion. A tidy picture of the particle zoo seemed to be emerging, except for some minor confusion concerning the muon. But here physicists George Rochester and Clifford Butler reported shocking evidence for yet further heavy particles of an unknown kind. They analysed photographs of energetic particles penetrating a cloud chamber, and in two cases noted V-like patterns apparently showing one incident massive particle spontaneously disintegrating into two others. These processes would later be identified as involving two new particles, the theta and tau particles: just two of a host of new particles to be discovered over the coming decades.

[中文](#)

AMONG some fifty counter-controlled cloud-chamber photographs of penetrating showers which we have obtained during the past year as part of an investigation of the nature of penetrating particles occurring in cosmic ray showers under lead, there are two photographs containing forked tracks of a very striking character. These photographs have been selected from five thousand

photographs taken in an effective time of operation of 1,500 hours. On the basis of the analysis given below we believe that one of the forked tracks, shown in Fig. 1 (tracks *a* and *b*), represents the spontaneous transformation in the gas of the chamber of a new type of uncharged elementary particle into lighter charged particles, and that the other, shown in Fig. 2 (tracks *a* and *b*), represents similarly the transformation of a new type of charged particle into two light particles, one of which is charged and the other uncharged. 中文

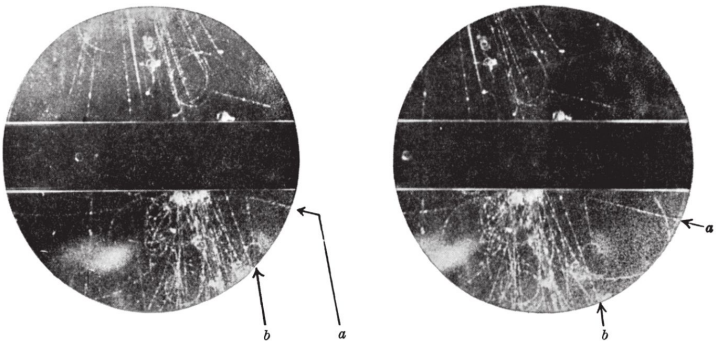


Fig. 1. Stereoscopic photographs showing an unusual fork (*a b*) in the gas. The direction of the magnetic field is such that a positive particle coming downwards is deviated in an anticlockwise direction 中文

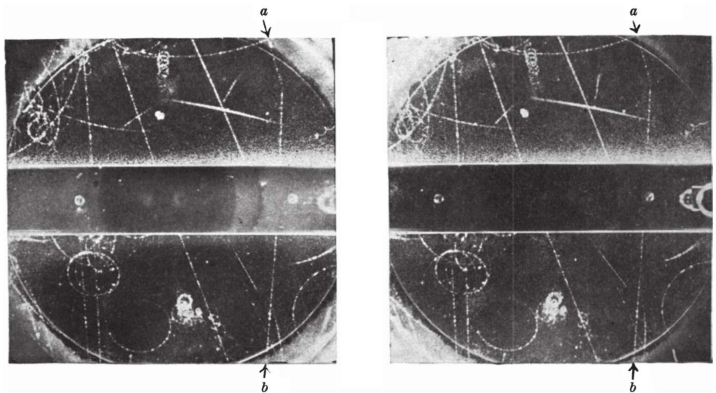


Fig. 2. Stereoscopic photographs showing an unusual fork (*a b*). The direction of the magnetic field is such that a positive particle coming downwards is deviated in a clockwise direction 中文

The experimental data for the two forks are given in Table 1; H is the value of the magnetic field, α the angle between the tracks, p and Δp the measured momentum and the estimated error. The signs of the

particles are given in the last column of the table, a plus sign indicating that the particle is positive if moving down in the chamber. Careful re-projection of the stereoscopic photographs has shown that each pair of tracks is copunctal. Moreover, both tracks occur in the middle of the chamber in a region of uniform illumination, the presence of background fog surrounding the tracks indicating good condensation conditions.

中文

Table 1. Experimental data

Photograph	H (gauss)	α (deg.)	Track	p (eV./c.)	Δp (eV./c.)	Sign
1	3,500	66.6	a	3.4×10^8	1.0×10^8	+
			b	3.5×10^8	1.5×10^8	—
2	7,200	161.1	a	6.0×10^8	3.0×10^8	+
			b	7.7×10^8	1.0×10^8	+

中文

Though the two forks differ in many important respects, they have at least two essential features in common: first, each consists of a two-pronged fork with the apex in the gas; and secondly, in neither case is there any sign of a track due to a third ionizing particle. Further, very few events at all similar to these forks have been observed in the 3 cm. lead plate, whereas if the forks were due to any type of collision process one would have expected several hundred times as many as in the gas. This argument indicates, therefore, that the tracks cannot be due to a collision process but must be due to some type of spontaneous process for which the probability depends on the distance travelled and not on the amount of matter traversed.

中文

This conclusion can be supported by detailed arguments. For example, if either forked track were due to the deflexion of a charged particle by collision with a nucleus, the transfer of momentum would be so large as to produce an easily visible recoil track. Then, again, the attempt to account for Fig. 2 by a collision process meets with the difficulty that the incident particle is deflected through 19° in a single collision in the gas and only 2.4° in traversing 3 cm. of lead—a most

unlikely event. One specific collision process, that of electron pair production by a high-energy photon in the field of the nucleus, can be excluded on two grounds: the observed angle between the tracks would only be a fraction of a degree, for example, 0.1° for Fig. 1, and a large amount of electronic component should have accompanied the photon, as in each case a lead plate is close above the fork. [中文](#)

We conclude, therefore, that the two forked tracks do not represent collision processes, but do represent spontaneous transformations. They represent a type of process with which we are already familiar in the decay of the meson into an electron and an assumed neutrino, and the presumed decay of the heavy meson recently discovered by Lattes, Occhialini and Powell¹. [中文](#)

The Masses of the Incident Particles

Let us assume that a particle of mass M and initial momentum P is transformed spontaneously into two particles of masses m_1 and m_2 , momenta p_1 and p_2 at angles of θ and φ with the direction of the incident particle. Then the following relations must hold:

$$\sqrt{M^2 c^4 + P^2 c^2} = \sqrt{m_1^2 c^4 + P_1^2 c^2} + \sqrt{m_2^2 c^4 + P_2^2 c^2} \tag{1}$$

$$P = p_1 \cos \theta + p_2 \cos \varphi \tag{2}$$

$$p_1 \sin \theta = p_2 \sin \varphi. \tag{3}$$

[中文](#)

These general relations may be used to obtain the mass of the incident particle as a function of the assumed masses of the secondary particles. [中文](#)

The value of M must be greater than that obtained by taking the rest masses of the secondary particles as small compared with their momenta; thus the minimum value $M_{\min}$ is given by the following

equation:

$$M_{\min} c^2 = c\sqrt{(p_1 + p_2)^2 - P^2}. \quad (4)$$

Applying this equation to the forked track of Fig. 1, after calculating P from the observed values of p_1 and p_2 , it is found that $M_{\min}$ is $(770 \pm 200)m$, where m is the mass of the electron. The application of equation (4) to the forked track of Fig. 2, however, after calculating p_2 from the observed values of P and p_1 , shows that $M_{\min} = (1,700 \pm 150)m$. This value of the mass would require an ionization for the incident particle of twice minimum, which is inconsistent with the observed ionization. We are therefore justified in assuming that the real value of P is greater than the observed value which, as indicated in Table 1, has a large error. If larger values of P are assumed, then $M_{\min}$ is reduced in value. The lowest value of $M_{\min}$ is $(980 \pm 150)m$ if P is 14.5×10^8 eV./c. Beyond this value of P the mass increases slowly with increasing momentum. No choice of incident momentum will bring the mass of the incident particle below $980m$. [中文](#)

In the special case where the incident particle disintegrates transversely into two particles of equal mass m_0 , giving a symmetrical fork, equation (1) reduces to the following expression,

$$\frac{M}{m} = \frac{2m_0}{m} \left(1 + \frac{p^2 c^2}{m_0^2 c^4} \cdot \sin^2 \theta \right)^{1/2}, \quad (5)$$

where p is the momentum of each of the secondary particles. Some typical results for different assumed secondary particles, calculated from equation (5), are given in Table 2. On the reasonable assumption that the secondary particles are light or heavy mesons, that is, with masses of $200m$ or $400m$, we find that the incident particle in each photograph has a mass of the order of $1,000m$. [中文](#)

Table 2. Mass of incident particle as a function of mass of secondary particle

Photograph	Assumed secondary particle m_0/m	Momentum of observed secondary particle (eV./c.)	Incident particle M/m
1	0	$3.5 \times 10^8 \pm 1.0 \times 10^8$	770 ± 200
	200	"	870 ± 200
	400	"	$1,110 \pm 150$
	1,837	"	$3,750 \pm 50$
2	0	$7.7 \times 10^8 \pm 1.0 \times 10^8$	980 ± 150
	200	"	$1,080 \pm 100$
	400	"	$1,280 \pm 100$
	1,837	"	$3,820 \pm 50$

中文

Upper values of the masses of the incident particles may also be obtained from the values of the ionization and the momenta. Thus for each of the observed particles in Fig. 1, the ionization is indistinguishable from that of a very fast particle. We conclude, therefore, that $\beta = v/c \geq 0.7$. Since the momentum of the incident particle may be found from the observed momenta of the secondary particles, we can apply equation (1) to calculate M . In this way we find $M/m \leq 1,600$. Again, since the ionization of the incident particle in Fig. 2 is light, $\beta \geq 0.7$, from which it can be shown that $M/m \leq 1,200$. This last result, however, must be taken with caution because of the uncertainty in the measured value of the momentum of the incident particle.

中文

One further general comment may be made. This is that the observation of two spontaneous disintegrations in such a small number of penetrating showers suggests that the life-time of the unstable particles is much less than the life-time of the ordinary meson. An approximate value of this life-time may be derived as follows. The probability of an unstable particle of life-time τ_0 decaying in a short distance D is given by

$$p = \frac{D(1-\beta^2)^{1/2}}{\tau_0 c \beta}. \tag{6}$$

Since the total number of penetrating particles in the penetrating showers so far observed is certainly less than 50, we must assume that

the number of our new unstable particles is unlikely to have been greater than 50. Since one particle of each type has been observed to decay, we can therefore put $p \approx 0.02$. Setting $D \approx 30$ cm., and $\beta = 0.7$, we find from equation (6) that $\tau_0 = 5.0 \times 10^{-8}$ sec. [中文](#)

We shall now discuss possible alternative explanations of the two forks. [中文](#)

Photograph 1. We must examine the alternative possibility of Photograph 1 representing the spontaneous disintegration of a charged particle, coming up from below the chamber, into a charged and an uncharged particle. If we apply the argument which led to equation (4) to this process, it is readily seen that the incident particle would have a minimum mass of $1,280m$. Thus the photograph cannot be explained by the decay of a back-scattered ordinary meson. Bearing in mind the general direction of the other particles in the shower, it is thought that assumption of the disintegration of a neutral particle moving downwards into a pair of particles of about equal mass is more probable. Further, it can be stated with some confidence that the observed ionizing particles are unlikely to be protons because the ionization of a proton of momentum 3.5×10^8 eV./c. would be more than four times the observed ionization. [中文](#)

Photograph 2. In this case we must examine the possibility of the photograph representing the spontaneous decay of a neutral particle coming from the right-hand side of the chamber into two charged particles. The result of applying equation (4) to this process is to show that the minimum mass of the neutral particle would be about $3,000m$. In view of the fact that the direction of the neutral particle would have to very different from the direction of the main part of the shower, it is thought that the original assumption of the decay of a charged particle into a charged penetrating particle and an assumed neutral particle is the more probable. [中文](#)

We conclude from all the evidence that Photograph 1 represents the decay of a neutral particle, the mass of which is unlikely to be less than $770m$ or greater than $1,600m$, into the two observed charged particles. Similarly, Photograph 2 represents the disintegration of a charged particle of mass greater than $980m$ and less than that of a proton into an observed penetrating particle and a neutral particle. It may be noted that no neutral particle of mass $1,000m$ has yet been observed; a charged particle of mass $990m \pm 12$ percent has, however, been observed by Leprince-Ringuet and L'héritier². 中文

Peculiar cloud-chamber photographs taken by Jánossy, Rochester and Broadbent³ and by Daudin⁴ may be other examples of Photograph 2.

中文

It is a pleasure to record our thanks to Prof. P. M. S. Blackett for the keen interest he has taken in this investigation and for the benefit of numerous stimulating discussions. We also wish to acknowledge the help given us by Prof. L. Rosenfeld, Mr. J. Hamilton and Mr. H. Y. Tzu of the Department of Theoretical Physics, University of Manchester. We are indebted to Mr. S. K. Runcorn for his assistance in running the cloud chamber in the early stages of the work. 中文

(160, 855-857; 1947)

G. D. Rochester and C. C. Butler: Physical Laboratories, University, Manchester.

References:

1. Lattes, C. M. G., Occhialini, G. P. S., and Powell, C. F., *Nature*, **160**, 453, 486 (1947).
2. Leprince-Ringuet, L., and L'héritier, M., *J. Phys. Radium*.(Sér. 8), **7**, 66, 69 (1946). Bethe, H. A., *Phys. Rev.*, **70**, 821 (1946).
3. Jánossy, L., Rochester, G. D., and Broadbent, D., *Nature*, **155**, 1 42 (1945). (Fig. 2. Track at lower left-hand side of the photograph.)
4. Daudin, J., *Annales de Physique*, 11^e Série, **19** (Avril-Juin), 1944 (Planche IV, Cliché 16).

新的不稳定基本粒子存在的证据

罗切斯特，布特勒

到1947年，物理学家们已经知道正电子和中微子，并刚刚发现了中性介子。除了关于 μ 介子存在一些小争议外，一个关于粒子园的令人满意的图景似乎已经成形了；但是在本文中物理学家乔治·罗切斯特和克利福德·布特勒报道了一种未知重粒子存在的证据，令人震惊。他们分析了穿透云室的高能粒子的照片，并在其中两张照片中注意到V形径迹，这显然表明一个有质量的入射粒子自发衰变为另外两种粒子。后来证实这些衰变过程与两种新粒子有关，分别是 θ 粒子和 τ 粒子，而它们仅仅是后来几十年中发现的大量新粒子中的两种。

[英文](#)

在过去的一年中，我们得到了约50张由计数器控制的贯穿簇射的云室照片，这些射线流是在对宇宙射线辐射铅板时，穿透铅板的粒子，照片是在研究穿透粒子的自然特征的实验中得到的，其中有两张具有显著的叉状特征。这些照片是从经过1,500个小时的有效工作中拍摄得到的5,000张照片中筛选出来的。在以下分析的基础上，我们相信其中图1中的一条叉状径迹（ a 、 b 径迹）代表了云室气体中的自发转变过程：一种新的不带电的基本粒子转化为更轻的带电粒子。而图2中的另一条径迹（ a 、 b 径迹）代表了相似的转变过程：一种新的带电粒子转化为两种轻粒子，其中一种粒子带电，另一种粒子不带电。

[英文](#)

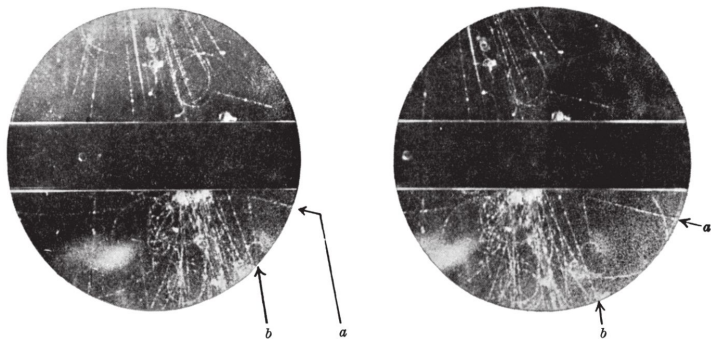


图1．立体照片显示了云室气体中一条不同寻常的叉状径迹（ $a\ b$ ）。磁场的方向使得向下运动带正电的粒子沿着逆时针方向发生偏转。[英文](#)

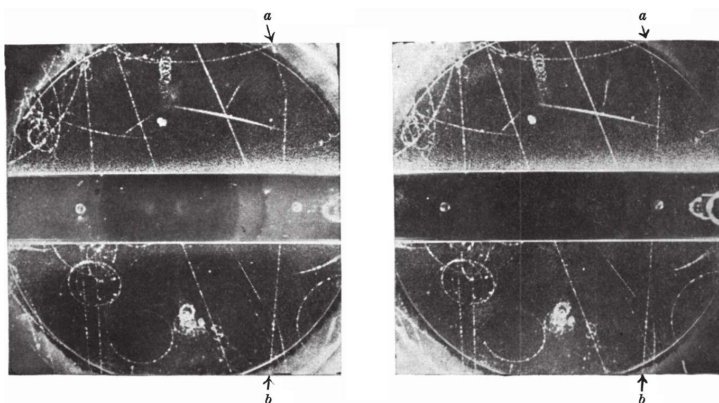


图2．立体照片显示了云室气体中一个不同寻常的叉状径迹（ $a\ b$ ）。磁场的方向使得向下运动带正电的粒子沿着顺时针方向发生偏转。[英文](#)

这两条叉状径迹的实验数据如表1所示。 H 为磁场的强度值， α 为叉状径迹的夹角， p 和 Δp 为动量的测量值和估计的误差值。在表格的最后一列给出这些粒子的符号，其中正号表示如果粒子穿过云室向下运动，则粒子带正电。对立体照片进行细致的重新投影发现，每一对径迹都是共点的。而且，每对中的两条径迹均出现在具有相同亮度的云室的中间区域，径迹周围雾化背景的存在表示该情况具有良好的凝聚状态。

[英文](#)

表1. 实验数据

照片	H (高斯)	α (度)	径迹	p (电子伏/光速)	Δp (电子伏/光速)	符号
1	3,500	66.6	a	3.4×10^8	1.0×10^8	+
			b	3.5×10^8	1.5×10^8	-
2	7,200	161.1	a	6.0×10^8	3.0×10^8	+
			b	7.7×10^8	1.0×10^8	+

[英文](#)

尽管这两条叉状径迹在很多重要的方面是不一样的，但它们具有至少两个相同的基本特征：第一，每一个都由两条叉状径迹组成，且尖端在气体中；第二，没有任何迹象表明任何一条径迹的符号是由第三个离子化的粒子引起的。另外，在3厘米厚的铅板的观测实验中几乎没有出现与这种叉状径迹相类似的情况。然而，如果叉状径迹是由任何一种类型的碰撞过程产生的，则预期在气体中能探测到的分叉应多几百倍。因此，以上讨论表明，这些径迹并不是由碰撞过程产生的，而是由某种自发过程引起的，而这种过程发生的概率依赖于粒子走过的路程而不是横向穿过粒子的数量。 [英文](#)

下面更细节的讨论将支持以上的结论。例如，如果叉状径迹的任意一支是由于带电粒子与核粒子碰撞发生偏转而产生的，动量的转移将足以产生一个清晰易辨的反冲径迹。这时，试图用碰撞过程来解释图2再次遇到了困难，即入射粒子在气体中的单个碰撞过程中偏离了 19° ，而在穿透3厘米铅板的过程中仅偏离了 2.4° ，这几乎是不可能的。基于以下两点考虑，我们可以排除在核子场中由高能光子产生电子对这种特有的碰撞过程：被观测到的叉状径迹之间的角度仅仅是1度的几分之一，例如图1中叉状径迹的角度只有 0.1° ；而且，在每次实验中铅板紧挨着叉状径迹的上方都应该有大量的电子伴随着光子出现，但事实上却没有发现大量电子的出现。 [英文](#)

因此，我们得出结论：这两条叉状径迹与碰撞过程无关，而是由自发转变过程产生的。它们代表了我们已经熟悉的介子衰变成电子和一种假定的中微子的过程，而且，最近拉特斯、奥恰利尼和鲍威尔^[1]已经观测到这种假想的重介子的衰变过程。 [英文](#)

入射粒子的质量

让我们假定质量为 M 、初始动量为 P 的一个粒子自发转化为两个粒子，这两个粒子的质量分别为 m_1 和 m_2 ，动量分别为 p_1 和 p_2 ，与入射粒子的夹角分别为 θ 和 φ ，则该过程应该满足以下关系式：

$$\sqrt{M^2 c^4 + P^2 c^2} = \sqrt{m_1^2 c^4 + P_1^2 c^2} + \sqrt{m_2^2 c^4 + P_2^2 c^2} \quad (1)$$

$$P = p_1 \cos \theta + p_2 \cos \varphi \quad (2)$$

$$p_1 \sin \theta = p_2 \sin \varphi \quad (3)$$

英文

这些普适的关系式可以用来求解入射粒子的质量，求得的解为假定的次级粒子质量的函数。 英文

假设次级粒子的静止质量相对于其动量来说很小，则真实的 M 值大小应该比在该假设极限情况下得到的解要大，因此 M 的最小值 $M_{\min}$ 可由下面的公式给出：

$$M_{\min} c^2 = c \sqrt{(p_1 + p_2)^2} - P^2 \quad (4)$$

通过测得的 p_1 和 p_2 值计算得出 P 之后，将以上公式用于求解图1中的叉状径迹，计算得到 $M_{\min}$ 为 $(770 \pm 200) m$ ，其中 m 为电子的质量。然而由观测得到的 P 和 p_1 值得出 p_2 后，将等式（4）用于求解图2中的叉状径迹，计算得到 $M_{\min} = (1,700 \pm 150) m$ 。这一质量值将对应于质量为两倍质量最小值的入射粒子发生电离，这与观测到的电离情况不一致。因此，我们有理由认为动量 P 的真实值大于测量值，正如表1中给出的那样，存在很大的误差。如果假定动量 P 的值更大，则 $M_{\min}$ 将会减小。如果 P 为 14.5×10^8 电子伏/光速，则 $M_{\min}$ 的最小值为 $(980 \pm 150) m$ 。当动量 P 超过这一值后，入射粒子的质量随着动量的增加而缓慢地增加。无论动量取何值，入射粒子的质量都不会低于 $980m$ 。 英文

在一个入射粒子分解为两个质量均为 m_0 的粒子的特定过程中，产生了一个对称的叉状径迹，而等式（1）将简化成以下表达式：

$$\frac{M}{m} = \frac{2m_0}{m} \left(1 + \frac{p^2 c^2}{m_0^2 c^4} \cdot \sin^2 \theta \right)^{1/2} \quad (5)$$

式中 p 为每个次级粒子的动量。对于不同的假定的次级粒子，由等式（5）计算得到的特定结果如表2所示。在次级粒子分别为质量 $200m$ 的轻介子或质量 $400m$ 的重介子的合理假定下，我们发现，每一张照片中

表2. 入射粒子质量与次级粒子质量的函数关系

照片	假定的次级粒子 m_0/m	探测到的次级粒子动量 (电子伏 / 光速)	入射粒子 M/m
1	0	$3.5 \times 10^8 \pm 1.0 \times 10^8$	770 ± 200
	200	"	870 ± 200
	400	"	$1,110 \pm 150$
	1,837	"	$3,750 \pm 50$
2	0	$7.7 \times 10^8 \pm 1.0 \times 10^8$	980 ± 150
	200	"	$1,080 \pm 100$
	400	"	$1,280 \pm 100$
	1,837	"	$3,820 \pm 50$

英文

上表中入射粒子的质量值也可以通过电离值和动量值计算得到。因此对于图1中观测到的每一种粒子，其电离情况与快粒子的电离情况是难以辨别的。因此，我们得出结论 $\beta=v/c\geq0.7$ 。既然入射粒子的动量可以由探测到的次级粒子的动量得出，我们就可以用公式（1）计算得出入射粒子的质量M。按这种方法分析，我们得到 $M/m\leq1,600$ 。此外，由于图2中入射粒子的电离结果是轻粒子， $\beta\geq0.7$ ，由此得到 $M/m\leq1,200$ 。然而，我们必须谨慎处理最后的结果，因为入射粒子动量的测量值具有不确定性。

英文

下面进行更深一步的全面讨论。即在这种少量的贯穿簇射中观测到的两个自发衰变表明，不稳定粒子的寿命要比普通介子的寿命短得多。下面的推导中将给出这个寿命的近似值。寿命为 τ_0 的不稳定粒子在短距离D范围内发生衰变的概率为：

$$p = \frac{D(1-\beta^2)^{1/2}}{\tau_0 c \beta}$$

(6)

目前为止探测到的贯穿簇射中贯穿粒子的总数量小于50，我们必须假设这种新的不稳定粒子的数目不可能大于50。由于观测发现每一种类型的粒子中都有一个粒子发生衰变，因此我们可以令 $p \approx 0.02$ 。取 $D \approx 30$ 厘米以及 $\beta = 0.7$ ，通过等式（6）我们可以得出 $\tau_0 = 5.0 \times 10^{-8}$ 秒。

英文

下面我们将讨论这两种叉状径迹另一种可能的解释。

[英文](#)

照片1 我们必须研究照片1所代表的另一种可能性：从云室的下方向上运动的带电粒子发生自发衰变，成为一个带电粒子和一个不带电粒子。如果我们将导出等式（4）的讨论应用到这一过程中，将会很容易地发现，入射粒子质量的最小值为 $1,280m$ 。因此，不能用普通的背散射介子的衰变来解释这张照片。考虑到簇射中其他粒子的一般方向，我们认为一个中性粒子向下移动，转化为具有相同质量的一对粒子这种假定的可能性比较大。进一步讲，我们有理由认为探测到的电离粒子不可能是质子，因为动量为 3.5×10^8 电子伏/光速的质子发生电离的结果将是实际探测到的电离结果的四倍多。

[英文](#)

照片2 在这种情况下，我们必须研究照片所代表的一种可能性：来自云室右边的一个中性粒子自发衰变为两个带电粒子。在这一过程中应用等式（4）得到的结果表明，中性粒子质量的最小值大约为 $3,000m$ 。鉴于实际情况为中性粒子的方向应该不同于簇射中大部分粒子的方向，因此认为一个带电粒子衰变为一个带电的贯穿粒子和一个中性粒子这种最初的假设可能性更大。

[英文](#)

通过所有的证据我们推断，照片1代表了一个质量介于 $770m$ 和 $1,600m$ 之间的中性粒子衰变为两个观测到的带电粒子的过程。类似的，照片2代表了质量大于 $980m$ 但小于质子质量的带电粒子衰变为观测到的贯穿粒子和中性粒子的过程。这里还必须声明，目前我们还没有探测到质量为 $1,000m$ 的中性粒子。然而，勒普兰斯-兰盖和莱里捷^[2]已经探测到一个质量为 $990m \pm 12\%$ 的带电粒子。

[英文](#)

由亚诺希、罗切斯特、布罗德本特^[3]以及多丹^[4]得到的特殊的云室照片可能是照片2中的其他情况。

[英文](#)

在这里感谢布莱克特教授对本项研究的极大关注及许多受益匪浅的讨论，感谢曼彻斯特大学理论物理学院罗森菲尔德教授、哈密顿先生和滋先生为我们提供的帮助，最后我们还要感谢朗科恩先生在本项研究工作的初期帮助我们操控云室。

[英文](#)

（胡雪兰 翻译；尚仁成 审稿）

A New Microscopic Principle

D. Gabor

Dennis Gabor was an employee of a large electrical manufacturer when he produced this paper, ostensibly directed at the improvement of the electron microscope but which has now become the principle underlying the technique called holography, by means of which all the information needed to construct a three-dimensional view can be stored on a two-dimensional surface, and which is widely used in devices such as bank and credit cards. Gabor moved to Imperial College London in the 1950s and received a Nobel Prize in 1971. [中文](#)

IT is known that the spherical aberration of electron lenses sets a limit to the resolving power of electron microscopes at about 5 Å. Suggestions for the correction of objectives have been made; but these are difficult in themselves, and the prospects of improvement are further aggravated by the fact that the resolution limit is proportional to the fourth root of the spherical aberration. Thus an improvement of the resolution by one decimal would require a correction of the objective to four decimals, a practically hopeless task. [中文](#)

The new microscopic principle described below offers a way around this difficulty, as it allows one to dispense altogether with electron objectives. Micrographs are obtained in a two-step process, by electronic analysis, followed by optical synthesis, as in Sir Lawrence Bragg's "X-ray microscope". But while the "X-ray microscope" is

applicable only in very special cases, where the phases are known beforehand, the new principle provides a complete record of amplitudes *and* phases in one diagram, and is applicable to a very general class of objects. [中文](#)

Fig. 1 is a broad explanation of the principle. The object is illuminated by an electron beam brought to a fine focus, from which it diverges at a semi-angle α . Sufficient coherence is assured if the nominal or Gaussian diameter of the focus is less than the resolution limit, $\lambda/2 \sin \alpha$. The physical diameter, determined by diffraction and spherical aberration of the illuminating system, can be much larger. The object is a small distance behind (or in front of) the point focus, followed by a photographic plate at a large multiple of this distance. Thus the arrangement is similar to an electron shadow microscope; but it is used in a range in which the shadow microscope is useless, as it produces images very dissimilar to the original. The object is preferably smaller than the area which is illuminated in the object plane, and it must be mounted on a support which transmits an appreciable part of the primary wave. The photographic record is produced by the interference of the primary wave with the coherent part of the secondary wave emitted by the object. It can be shown that, at least in the outer parts of the diagram, interference maxima will arise very nearly where the phases of the primary and of the secondary wave have coincided, as illustrated in Fig. 1. [中文](#)

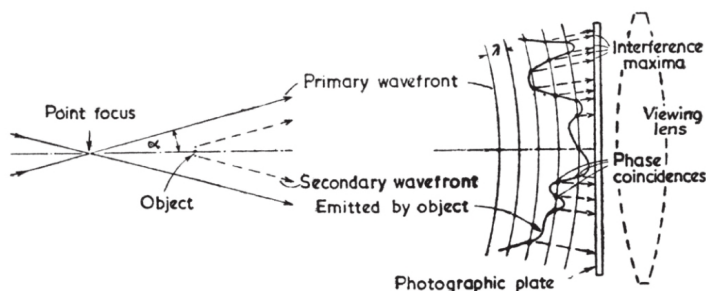


Fig. 1. Interference between homocentric illuminating wave and the secondary wave emitted by a small object [中文](#)

If this photograph is developed by reversal, or printed, the loci of maximum transmission will indicate the regions in which the primary wave had the same phase as the modified wave, and the variations of the transmission in these loci will be approximately proportional to the intensity of the modified wave. Thus, if one illuminates the photographic record with an optical imitation of the electronic wave, only that part of the primary wave will be strongly transmitted which imitates the modified wave both in phases and in amplitudes. It can be shown that the “masking” of the regions outside the loci of maximum transmission has only a small distorting effect. One must expect that looking through such a properly processed diagram one will see behind it the original object, as if it were in place. 中文

The principle was tested in an optical model, in which the interference diagram was produced by monochromatic light instead of by electrons. The print was replaced in the apparatus, backed by a viewing lens which admitted about $\sin \alpha = 0.04$, and the image formed was observed and ultimately photographed through a microscope. It can be seen in Fig. 2 that the reconstruction, though imperfect, achieves the separation of some letters which could just be separated in direct observation of the object through the same optical system. The resolution is markedly imperfect only in the centre, where the circular frame creates a disturbance. Other imperfections of the reconstruction are chiefly due to defects in the microscope objectives used for the production of the point focus, and for observation. 中文

It is a striking property of these diagrams that they constitute records of three-dimensional as well as of plane objects. One plane after another of extended objects can be observed in the microscope, just as if the object were really in position. 中文

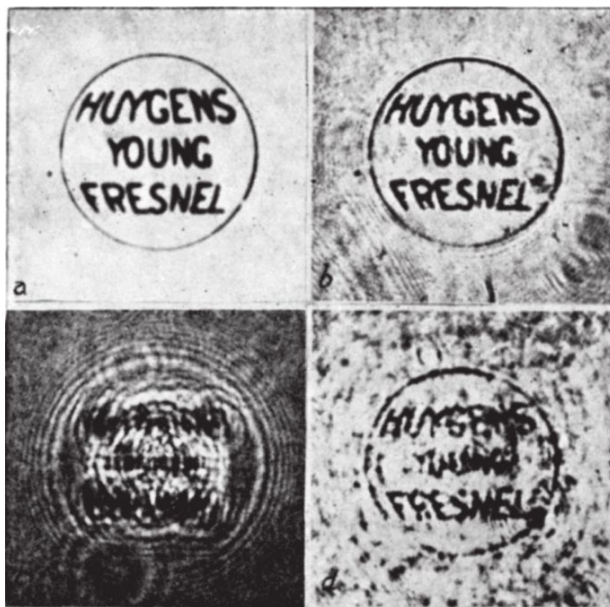


Fig. 2. (a) Original micrograph, 1.4 mm. diameter. (b) Micrograph, directly photographed through the same optical system which is used for the reconstruction (d). Ap. 0.04. (c) Interference diagram, obtained by projecting the micrograph on a photographic plate with a beam diverging from a point focus. The letters have become illegible by diffraction. (d) Reconstruction of the original by optical synthesis from the diagram at the left. To be compared with (b). The letters have again become legible 中文

Racking the microscope through and beyond the point focus, one finds a second image of the original object, in central-symmetrical position with respect to the point focus. The explanation is, briefly, that the photographic diagram cannot distinguish positive and negative phase shifts with respect to the primary wave, and this second image corresponds to the same phase shifts as the original, but with reversed sign. 中文

If the principle is applied to electron microscopy, the dimensions in the optical synthesizer ought to be scaled up in the ratio of light waves to electron waves, that is, about 100,000 times. One must provide an illuminating system which is an exact optical imitation of the electronic condenser lens, including its spherical aberration. To avoid scaling-up the diagram, one has to introduce a further lens, with a focal length equal to the distance of the object from the photographic

plate in the electronic device, in such a position that the plate appears at infinity when viewed from the optical space of the point focus. Work on the new instrument, which may be called the “electron interference microscope”, will now be taken in hand. [中文](#)

I wish to thank Mr. I. Williams for assistance in the experiments, and Mr. L. J. Davies, director of research of the British Thomson-Houston Company, for permission to publish this note. [中文](#)

(161, 777-778; 1948)

D. Gabor: Research Laboratory, British Thomson-Houston Co., Ltd., Rugby.

一种新的显微原理

盖伯

丹尼斯·盖伯在完成这篇论文时还是一家大型电子制造企业的一名雇员，表面上这篇论文指导了电子显微镜的改进，而如今，这篇论文业已成为全息摄影技术的原理。这项技术可以将构造三维影像所需的全部信息储存于二维表面中，并已广泛应用于银行和信用卡等设备中。20世纪50年代盖伯进入伦敦帝国学院，并于1971年获得诺贝尔奖。 [英文](#)

我们已经知道，电子透镜的球差决定了电子显微镜的分辨率极限约为5埃。虽然人们已经提出建议对物镜进行校正，但是这些都很难实现，而分辨率极限正比于球差的四次方根这一事实使得改进分辨率的希望更为渺茫。也就是说，要将分辨率提高10倍，需要将物镜的校正提高一万倍，这几乎是一项不可能完成的任务。 [英文](#)

下面所描述的新的显微原理提供的方法可绕过上述困境，因为它完全无需使用电子物镜。可通过两步处理获得显微图像，即电子分析和随后的光学合成，就像劳伦斯·布拉格爵士的“X射线显微镜”那样。但是“X射线显微镜”只适用于那些预先知道相位的非常特殊的情况，而新原理则在一张图像中提供了振幅和相位的完整记录，因而适用于极其一般的各类物体。 [英文](#)

图1是对该原理的一个概括性解释。用一束向细微焦点聚焦后并以半角 α 发散的电子束照明物体。如果焦点的标称直径或高斯直径小于分辨率极限值 $\lambda/2 \sin \alpha$ ，就能确保充分的相干性。由照明系统的衍射和球差所决定的物理直径可能还要大得多。物体位于焦点后方（或前方），与焦点相隔很小的一段距离，在其后面比这段距离大很多倍的位置放置照相干板。因而这样的排列方式与电子阴影显微镜类似；但是它可以在

阴影显微镜力不能及的范围使用，因为它会产生与初始图像截然不同的图像。物体最好小于物平面中的照明面积，而且必须被固定在一个可透射相当一部分初级波的支架上。通过初级波与物体发出的次级波中的相干部分之间的干涉产生照相记录结果。可以看到，至少在图像靠外的区域中会出现干涉极大，其位置非常接近于图1所示的初级波相位和次级波相位达到一致的位置。

英文

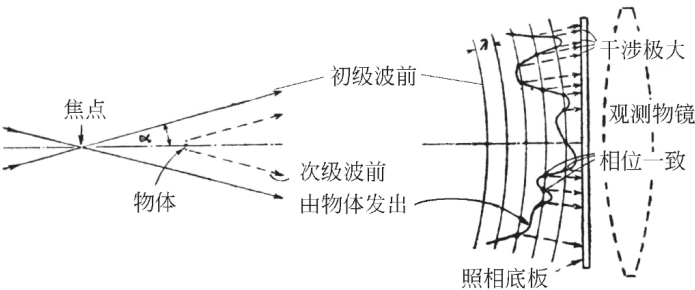


图1．共心照明波与微小物体发出的次级波之间的干涉

英文

如果将照片进行反转处理或者翻印出来，最强的透射位点就代表了初级波（译者注：“初级波”的一部分被用作物体的照明光；另一部分，即其未被物体散射的部分被用作参考光）与修正波（译者注：“修正波”是“初级波”照射在物体上，被物体散射而发生改变的波，也就是“物波”）具有相同相位的区域，而这些位置上透射率的变化将近似正比于修正波的强度变化。因此，如果用电子波的光学模拟去照射照相记录，只有能够同时模拟修正波的相位和振幅的部分初级波才会被强烈透射。可以看出，对最强透射位置之外区域的“掩蔽”只会产生小的扭曲效应。应该可以预期，通过仔细查看这类经过适当处理的图像，我们将会看到它背后的原物体，好像它就在眼前一样。

英文

可用一个光学模型来检验这一原理，即用单色光而不是电子产生干涉图像。将装置中的照片放回原处，背后加一面观测物镜，它允许的入射半角近似为 $\sin \alpha = 0.04$ ，通过一台显微镜观察所形成的图像并最终进行拍照。在图2中可以看到，虽然重现影像并不完美，但是利用相同的光学系统直接观察物体时刚好可以区分的那些字母，在重现影像中也能够被区分。只有中心部分的分辨率明显不足，那是圆框造成了干扰。重现影像的其他不足主要是由用以产生焦点和进行观测的显微镜物镜的瑕疵导致的。

英文

这些图像具有一个引人注目的特性，即它们能像记录平面物体一样地记录三维物体。可以在显微镜中逐一地连续观察延伸物体的不同平面，就好像它们真的在那个位置一样。 英文

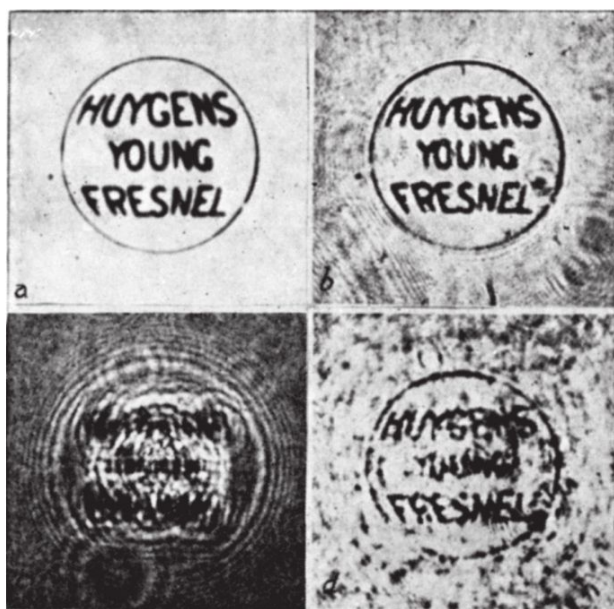


图2. (a) 原始显微图，直径为1.4毫米。(b) 显微图，通过直接照相得到，与重现影像(d)使用相同的光学系统。Ap. 0.04。(c) 干涉图，利用从一个焦点发散出来的射线束将显微图投影于照相干板上得到。字母由于衍射而变得模糊。(d) 利用光学合成从左侧图像得到的重现影像。以(b)为参照，字母再度由模糊变得清晰。

编者注：图中所使用的三个人名Huygens（惠更斯）、Young（杨）、Fresnel（菲涅耳）代表证明光的波动性的三位重要科学家。 英文

将显微镜经过焦点向另一侧移动，我们会在相对于该焦点中心对称的位置发现原物体的第二个像。对此现象的简要解释是，照相图像无法区分初级波的正相移与负相移，这第二个像与原物体的相移相同，但是符号相反。 英文

如果将该原理应用于电子显微镜，那么在光学合成仪器中的尺度应该按光波对电子波的比值（即大约100,000倍）同比例增加。同时必须提供一个照明系统，它是电子聚焦透镜及其球差的严格光学模拟。为避免图像按比例增大，还必须再引入一个透镜，其焦距等于从电子装置中的照相干板到物体之间的距离，其放置位置应使得从焦点的光学距离看来干板出现在无穷远处。对于这种我们不妨称为“电子干涉显微镜”的新

型装置的研究即将展开。 英文

我要感谢威廉姆斯先生在实验中给予的协助，感谢英国汤姆森-休斯敦电气公司研究主管戴维斯先生对这篇短文的公开发表给予允准。

英文

（王耀杨 翻译；熊秉衡 审稿）

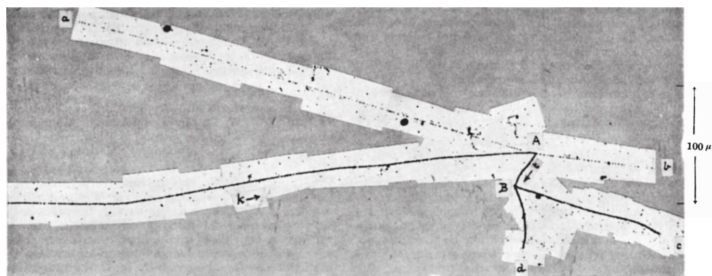
Observations with Electron-sensitive Plates Exposed to Cosmic Radiation

R. Brown *et al.*

Inspired by recent evidence of new particles having a mass approximately 1,000 times that of the electron, physicist Cecil Powell and colleagues here report on high-altitude cloud-chamber experiments on cosmic rays: high-energy particles coming from space. They analyse one track from a particle having unit charge, called a “*k*-particle” (later a kaon), which entered the chamber and subsequently decayed into two other particles. Estimating the *k*-particle’s mass by counting photographic grains, they found a value of roughly 1,080 times the electron mass. They interpret its decay as a process involving the creation of two particles called pions. These discoveries led towards the discovery, within a decade, that interactions involving the weak nuclear force do not respect mirror symmetry. [中文](#)

ONE of the first events found in the examination of electron-sensitive plates exposed at the Jungfrauoch is represented in the mosaic of photomicrographs shown in Fig. 8. There are two centres, *A* and *B*, from which the tracks of charged particles diverge, and these are joined by a common track, *t*. Because of the short duration of the exposure, and the small number of disintegrations occurring in the

plate, the chance that the observation corresponds to a fortuitous juxtaposition of the tracks of unrelated events is very small—of the order 1 in 10^7 . It is therefore reasonable to exclude it as a serious possibility. Further observations in support of this assumption are presented in a later paragraph. 中文



Observer: Mrs. W.J. van der Merwe

Fig. 8 中文

An inspection of the track *k* shows that the particle producing it approached the centre of disintegration *A*. The range of the particle in the emulsion exceeds $3,000\ \mu$, and there is continuous increase in the grain-density along the track in approaching *A*. Near *A*, the grain-density is indistinguishable from that of particles of charge *e*, recorded in the same plate, near the end of their range. 中文

The evidence for the direction of motion of the particle based on grain-counts is supported by observations on the small-angle deviations in the track due to Coulomb scattering. These deviations are most frequent near *A*, and the scattering is less marked at points remote from it. 中文

From these observations, it is reasonable to conclude that the particle *k* approached the point *A*; that it carried the elementary electronic charge and that it had reached, or was near, the end of its range at the point *A*. We therefore assume that the particle *k* initiated the train of events represented by the tracks radiating from *A* and *B*. It follows that the particle producing track *t* originated in star *A*, and produced the disintegration *B*. In order to analyse the event, we first attempted

to determine the mass of the particle k . [中文](#)

Mass Determinations by Grain-Counts

About a year ago, experiments were made in this Laboratory to determine the ratio, m_{π}/m_{μ} , of the masses of π - and μ -mesons, by the method of grain-counting⁵, and by studying the small-angle scattering of the particles in their passage through the emulsion⁴. The values obtained by the two methods were $m_{\pi}/m_{\mu} = 1.65 \pm 0.11$, and $m_{\pi}/m_{\mu} = 1.35 \pm 0.10^*$, respectively. Recent experiments at Berkeley⁶ suggest that the true value is 1.33 ± 0.02 , a result which throws serious doubt on the reliability of the method based on grain-counts. Because of the advantage of this method, and of the important conclusions which have been based on it, experiments were made to determine the conditions in which reliable results can be obtained.

[中文](#)

In the first experiments⁵, the two most serious experimental difficulties arose from the fading of the latent image and from the variation of the degree of development with depth. This made it necessary to work only with tracks formed contemporaneously; to compare the grain-density along the tracks of the π - and μ -mesons of the same pair. As a result, the tracks of the π -mesons available for measurement were, in most cases, shorter than 400 μ . In continuing the experiments, much more favourable conditions were obtained by using short exposures, so that the effects of fading were negligible; and by developing the plates by the method employed by Dilworth, Occhialini and Payne⁷, which gives a nearly uniform degree of development with depth. [中文](#)

In the plates obtained by these methods, it is legitimate to compare the grain-density in the tracks of unrelated particles. Further, it is now known that at least the majority, and possibly all, the mesons which produce "stars" are π^- -particles^{6,8}; and that most of the ρ -mesons are

μ^+ - and μ^- -particles. In determining m_π and m_μ , we have therefore made measurements on the tracks of π^+ - and π^- -, μ^+ - and μ^- -particles, of length greater than 1,000 μ , comparing the results with those of similar measurements made on the tracks of protons. In these conditions, we have found $m_\pi/m_\mu = 1.33 \pm 0.05$. A detailed account of the observations will be published elsewhere; but, for the purpose of the present paper, it is sufficient to note that the results appear to be in good accord with those obtained by other methods. We conclude that, using the Ilford C2 emulsion in the new conditions, reliable information can be obtained. [中文](#)

We have seen that the conditions of uniform development and absence of fading have been achieved in the present experiments with the new Kodak emulsions, and we therefore attempted to measure the mass of particles by similar methods to those employed with the Ilford plates. The results obtained in observations on the tracks of four protons and four μ -particles, occurring in the same plate, are represented in Fig. 9. In this figure, the number of grains per unit length in the tracks is plotted for different values of the residual range; and the mean values, for tracks of the same type, are indicated by the full lines. The ratio of the masses of the two types of particles can be deduced by making a comparison of the values of the residual range at which the grain densities have the same value. The result thus obtained is $m_\mu = 220 \pm 20 m_e$. [中文](#)

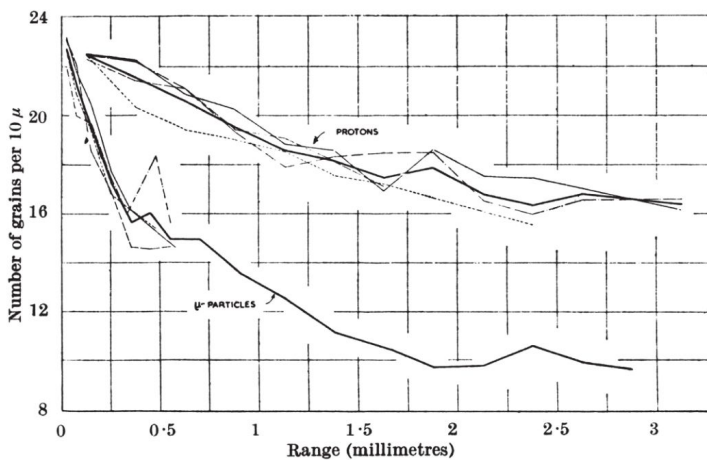


Fig. 9 中文

Using similar methods, we have made estimates of the mass of the particle, k , and the measurements are represented in Fig. 10. This figure shows the mean values of the grain-density in the tracks of the four μ -mesons and four protons, together with the corresponding results for the particle k . All the tracks under consideration occurred in the same plate. 中文

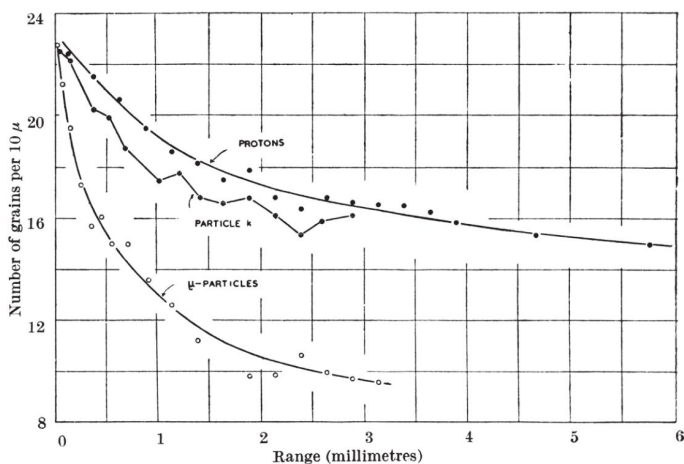


Fig. 10 中文

Table 1 shows the values of the mass of the particle, k , as determined from these results, by making a comparison of the grain-density in the track of the particle with the mean curve for protons. The values thus obtained are all independent and the mean is $m_k = 1,080 \pm 160 m_e$.

Table 1. Determination of the ratio, m_p/m_k , of the mass of a proton to that of particle, k , by grain-counting

Individual independent values							
m_p/m_k	1.77	1.88	1.49	1.64	2.17	1.79	1.32
	1.71	1.66	1.27	1.69	2.13	1.55	
Mean value: $1.70; m_k = 1,080 \pm 160 m_e$							

中文

The limits of error given above have been deduced in the following manner: We have compared the grain-density in the tracks of the four individual protons with the mean curve for the same particles—(see Fig. 9)—and have thus obtained a number of independent values for the apparent mass of each of these particles. The distribution in these values allows us to calculate the “probable error” associated with the mass as determined from the observations on any one track, expressed as a percentage of the apparent mass of the particle. It is then assumed that the “probable” percentage error in the calculated mass of the particle k has the same value. 中文

We have also determined the mass m_k by studying the small-angle scattering of the particle, by the methods recently described⁴, and the result thus obtained is $m_k = 1,800 \pm 400 m_e$. If the true mass of the particle is $1,080 m_e$, the chance that the value obtained by observations on scattering shall be equal to, or greater than, $1,800 m_e$ is one in four. Because of the large statistical fluctuations associated with the observations in the scattering experiments, we give more weight to the measurements by grain-counting. It appears certain, from these observations, that the true value of m_k lies between 700 and $1,800 m_e$, and we think it highly probable that it is substantially less than that of the proton. Thus every individual point representing the grain-density in the track k , at a particular value of the residual range, lies below the corresponding points for each of the four protons. 中文

Disintegration “B”

The tracks, c and d , of the two particles emitted from point B are characteristic of protons or heavier particles, and we regard them as due to a disintegration produced by the particle t . This particle was frequently scattered in passing through the emulsion and was therefore of low velocity; and the evidence is consistent with the assumption that it had reached the end of its range at the point B .

中文

The only known slow charged particle which is capable of producing a disintegration of the type represented by star B is a π^- -particle^{6,8}. We therefore assume that a negative meson of mass $286 m_e$ was created at the point A , and reached the end of its range to produce the disintegration B .

中文

Transmutation “A”

In order to interpret the transmutation A , we first made a detailed examination of the tracks of the emitted particles. Of the two tracks a and b , the former has a length in the emulsion of more than $2,000 \mu$, and ends in the surface, whereas b ends in the glass and is 116μ long. The grain-densities in the two tracks are equal to within the limits defined by the statistical fluctuations. The average grain-density in the long track a is 49.0 grains per 100μ ; that is, 2.17 times the value characteristic of minimum ionization for a particle of charge e . Unless we admit the existence of fractional values of the electronic charge, we must conclude that the particles producing the tracks a and b both carried charges of magnitude e .

中文

In order to determine the possible values for the energy of the particles producing tracks a and b , we have calculated the variation with energy of the specific ionization of a particle of charge e , from the formula of Halpern and Hall⁹, assuming the atomic composition of

the emulsion to be identical with that of the Ilford C2 plates. This formula is a modification of that of Bloch¹⁰; it applies to particles moving in a solid medium and gives results in good agreement with experiment for particles of low energy. The results are shown in Fig. 11, where the specific ionization is plotted as a function of the quantity E/m , where E is the energy and m the mass of the particle, both quantities being measured in MeV. From Fig. 11, we have determined the possible values of the energy of the particles, a , b , corresponding to the observed grain-density in the tracks, assuming them to be protons, π -mesons, μ -mesons or electrons. The resulting values are tabulated in Table 2. 中文

Table 2. Values of the energy and momentum of the particle producing track a , as deduced from the observed grain-density and scattering, making various assumptions concerning the mass of the particle

Assumed particle		proton	π -meson	μ -meson	electron
Energy in MeV.	(a) below minimum ionization	235±95	37±13	27±11	0.13±0.05
	(b) above minimum ionization				>1,000
Momentum MeV/c	(a) below minimum ionization	700±160	109±22	80±15	0.4±0.1
	(b) above minimum ionization				>1,000
	(c) from scattering observations	245±40	113±18	100±16	68±11
	(d) from momentum balance	98±5	98±5	98±5	98±5

中文

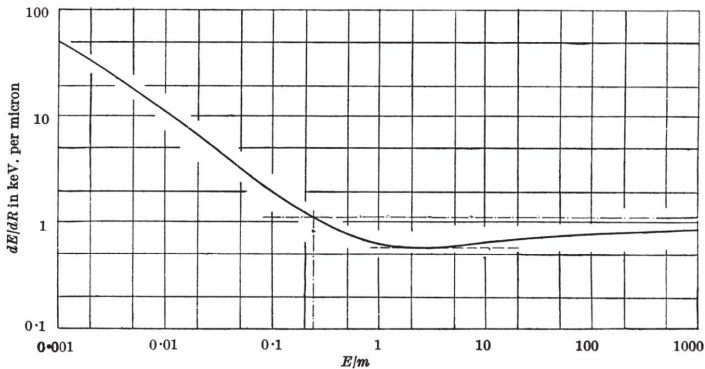


Fig. 11. Variation of the rate of loss of energy of a particle of charge $|e|$ as a function of the

quantity E/m , where E is the kinetic energy and m the mass of the particle, both quantities being measured in MeV. [中文](#)

There are two possible interpretations of the transmutation produced at A by the particle k . We can assume, either that the particle was captured by a nucleus, or that it decayed spontaneously. From the measured values of the mass of the particle, it would be possible, from the point of view of the conservation of mass and energy, to admit that, at the end of its range in the emulsion, it was captured by a nucleus and led to the ejection of two energetic protons and a π^- -particle. It appears almost certain, however, that the release in a nucleus of such a large amount of energy would lead to the “evaporation” of many nucleons, a process commonly observed in plates exposed to the cosmic radiation; and that two protons of great energy would be only two components of a “many-pronged” star. (It may be noticed that we cannot assume that the particle k was captured by one of the rare nuclei of heavy hydrogen, present in the gelatine. In such an interaction, the algebraic sum of the charges on the two initial particles is 0 or $2e$, whereas that of the product particles is e or $3e$.) We shall see later that there are other objections to the hypothesis that the tracks a and b were produced by protons, or heavier nuclei of charge e . [中文](#)

It follows from the above considerations that if we are to describe the transmutation in terms of particles of which the existence is already established, we must attribute the tracks a and b either to electrons, to μ -mesons or to π -mesons. Considering the first of these possibilities, we must assume the electrons to have had an energy value greater than that corresponding to minimum ionization, namely, greater than 1,000 MeV.; for with the alternative lower value corresponding to the observed ionization, 300 keV., the particle would have had a range in the emulsion of only about 100 μ , and would have been frequently scattered. The assumption that the particles a and b were electrons is therefore inconsistent with the conservation of energy and can be

rejected. We are left with the alternatives that the tracks were produced either by π^- or by μ^- -mesons. 中文

If the particles a and b were mesons, we must assume, in order to conserve mass-energy, that their kinetic energies were 27 MeV. or 37 MeV., respectively, in the case of μ^- or π^- -mesons (see Fig. 11). In either case, it appears to be very difficult to reconcile the observations with the assumption that the particles were emitted as a consequence of the liberation in a nucleus of the energy corresponding to the rest-mass of particle k . We are therefore led to examine the possibility of explaining the observations in terms of a spontaneous decay of this particle. 中文

Assumption of a Spontaneous Decay of the k -Particle

In examining the possibility that the transmutation A corresponds to a spontaneous decay of the particle k , we require to know the relative directions of motion of the three ejected particles. For this purpose it is necessary to determine the shrinkage of the emulsion; the ratio, S , of the thickness of the emulsion during exposure to that after it had been developed, fixed and dried. We have measured this quantity by examining the tracks of α -particles, produced in the emulsion by uncontrolled radioactive contamination. Among such “stars”, it is possible to identify some, due to an original atom of radiothorium, from which an α -particle of thorium C' was emitted. The shrinkage has been measured by determining the lengths of the projection of the corresponding tracks on the surface of the emulsion, and their apparent angles of “dip”. The value of the “shrinkage” thus found is $S = 2.7 \pm 0.1$. Knowing the value of S , the original orientation of a track in the emulsion, before processing, can be determined, in favourable cases, with a precision of the order of 1° , by observing the apparent angle of “dip” of the particle, and the direction of its projection on the plane defined by the surface of the emulsion. Using these methods, the original directions of motion of the three particles a , b and t were

found to be coplanar. The departure of the direction of motion of any one particle from the plane defined by the other two is less than 4° . The error in this determination is largely due to the fact that track t is of short range, and the particle producing it was of low velocity, and frequently scattered. 中文

The values of the angles between the directions of motion of the particles in the common plane are shown in Fig. 12. The observed coplanarity makes it legitimate to assume that the three particles arise as a result of the spontaneous decay of the k -particle at the end of its range in the emulsion, and that they are the only product of its disintegration; that no neutral particles, which would escape observation, are emitted. It follows that the vector sum of the momenta of the three particles must be assumed to be equal to zero.

中文

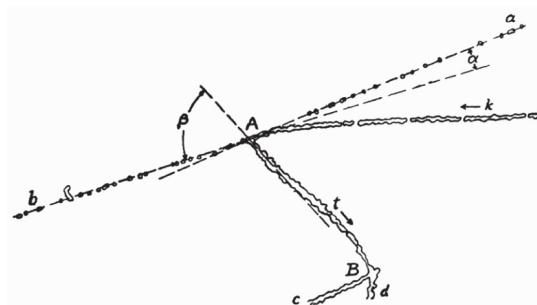


Fig. 12. Facsimile drawing of the event shown in Fig. 8, made with the projection microscope. The actual angles α and β , measured in the common plane of the three tracks, a , b and t , are: $\angle\alpha = 9.8^\circ$; $\angle\beta = 76.6^\circ$ 中文

If we are correct in attributing the track t to a π^- -particle, it follows from the observed range, $45\ \mu$, that the kinetic energy of ejection was 1.04 MeV. The corresponding value of the momentum of the particle is $17.5\ \text{MeV.}/c$. From the observed directions of motion, the momenta of the particles giving tracks a and b are then found to be 98 ± 5 and $104 \pm 5\ \text{MeV.}/c$, respectively. These values are to be compared with those corresponding to electrons or mesons listed in Table 2, which have been deduced from the observed grain-density in the tracks. We

have seen that the values given in Table 2 for the momenta of the two particles, if they are assumed to be electrons, are many times too large. It follows that there is a wide departure from a momentum balance if the tracks a and b are assumed to be due to either electrons or protons. Further, the values of the momenta, as deduced from observations on the scattering of the particles, are inconsistent with those obtained from grain-counts, if the particles are assumed to have been either electrons or protons (see Table 2). [中文](#)

The agreement between the sets of values for mesons, however, is most remarkable, and gives strong support for the assumption of a spontaneous decay of the k -particle. Only a very rare combination of unrelated features, including the co-planarity of the tracks and the directions of motion of the particles in the common plane, the range of the particle t , and the specific ionization of the particles producing tracks a and b , could produce such an agreement between the estimated values of the momenta, if the result is fortuitous. [中文](#)

The values of the momenta of the particles producing tracks a and b , as determined by the three different methods, are consistent, within the errors of measurements, with the assumption of a spontaneous decay of the k -particle whether the product particles are assumed to be μ -mesons or π -mesons. We can apply a further test by calculating the values of the rest-mass of the particle k which corresponds to the two different assumptions, and the results are tabulated in Table 3. [中文](#)

Table 3. Estimates of the mass of particle k based on total release of mass and energy, for two assumed modes of decay

(i) $k \rightarrow \pi^- + \pi + \pi$			
	Track "a"	Track "b"	Track "f"
Particle	π	π	π^-
Rest-mass (m_e)	286	286	286
Energy in m_e	61	64	2
Total = $m_k = 985\ m_e$			
(ii) $k \rightarrow \pi^- + \mu + \mu$			
Particle	μ	μ	π^-
Rest-mass (m_e)	212	212	286
Energy in m_e	76	81	2
Total = $m_k = 869\ m_e$			

In calculating the energy of the particles producing tracks *a* and *b*, it is assumed that the particle producing track *t* is a π^- -particle, of momentum 17.5 MeV./c; knowing the relative directions of motion of the three ejected particles, the momenta of the other two particles are determined, and hence the energies corresponding to any assumed mass. 中文

It will be seen from Table 3 that the assumption of two μ -mesons corresponds to a rest mass of the *k*-particle of 869 m_e ; and for two π -mesons, 985 m_e . The assumption of different particles, one π^- and one μ -meson, gives an intermediate value of approximately 925 m_e . In view of the error in the direct determination of m_k , the results are not decisive. 中文

If the transmutation is to be interpreted in terms of particles of which the existence is already established, we are left with four possibilities for the nature of the particles producing tracks *a* and *b*. These are indicated schematically in Table 4. 中文

Table 4. Comparison of the observed and calculated values of the grain-density in track *b*, for various assumptions regarding the nature of the particles producing the tracks *a* and *b*

	Length of track in microns	Number of grains	Grain-density	Assumed particles			
				1	2	3	4
Track <i>a</i>	2,100	1,025	49±1.5	π	μ	π	μ
Track <i>b</i>	116	59	51±6	π	μ	μ	π
Calculated grain-density in <i>b</i>				45	45	34	64

Values of the grain-density are given in grains per 100 μ . 中文

For the following reasons, case 3, Table 4, is the most improbable. If track *a* is that of a π -meson, we can calculate the momentum and the grain-density to be expected in track *b*. We thus obtain the value of 34 grains per micron instead of 51.0 ± 6.0 as observed. For case 4, on the

other hand, if a is a μ -meson, the calculated grain-density for track b is 64, a value which differs from that observed by an amount only twice that corresponding to the standard deviations. The observed grain-densities agree best with the assumption that the two particles are of the same type. [中文](#)

Observations on the scattering of the particle producing track a are in better accord with the assumption that it is a π -meson rather than a μ -meson (see Table 2); but the results are again indecisive. We may sum up this evidence, and that provided by the mass determinations by grain-counting, by saying that there is some support for the view that the three product-particles are π -mesons; but that the alternative possibilities of one π - and two μ -, or two π - and one μ -meson cannot be excluded. [中文](#)

Chance Juxtaposition of Unrelated Events

In the light of the analysis made in the preceding sections, we can now return to the original assumption that the event is not to be regarded as a fortuitous juxtaposition of tracks. The accuracy of the determination of the mass of the particle k does not allow us to exclude the possibility that it has a mass as great as that of a proton, although the observations by grain-counts render it very improbable. Suppose then that a proton, unrelated to the particles producing the other tracks, came to the end of its range at A . Even with this assumption, the event is still difficult to explain in conventional terms. Many examples of π^- -particles ejected from stars have been observed in this Laboratory⁸, but in the present instance the existence of a nuclear interaction in which two protons of great energy are emitted, unaccompanied by slow protons and α -particles, would remain to be explained. A similar difficulty is met if we assume that a particle producing one of the tracks, a or b , approached A and produced the transmutation. [中文](#)

If, alternatively, the tracks c and d , diverging from star B , represent an unrelated disintegration—produced, for example, by a γ -ray—we could then assume track t to be that of a proton. We are then left with the difficulties associated with the features peculiar to star A , which must now be assumed to have been produced by a slow, charged particle; difficulties which have already been discussed in a previous paragraph. These considerations give further support to the original assumption, that all the tracks shown in the mosaic represent a succession of associated processes. 中文

Relation of the Present Results to Other Observations

If a particle with the elementary electronic charge suffers a spontaneous decay, the law of the conservation of charge demands that the number of emitted particles of charge e shall be odd. From this point of view, the sign of the charge of the original particle can have been either positive or negative. If the particles producing tracks a and b form a pair of opposite sign, then the original k -particle was negative. The only other alternative is that they were both positively charged, in which case the k -particle was also positive. It is therefore possible that our observations correspond to a mode of decay of positive particles of mass approximately $900 m_e$, and that the observation by Leprince-Ringuet² demonstrates the fate of the corresponding negative particles—nuclear capture with the production of a “star” and the ejection of a π^- -particle. 中文

Rochester and Butler² have published an expansion-chamber photograph which appears to be due to the spontaneous decay of a neutral particle of mass approximately $900 m_e$ into a pair of oppositely charged particles of rest-mass approximately $300 m_e$. We have therefore considered the possibility that the decay process suggested by the present results can be regarded as taking place in two stages: the emission of a π^- -particle of low energy, followed by the spontaneous decay of the resulting neutral particle. On this view,

however, it would be necessary to assume that the neutral particle has a life-time of the order of 10^{-14} sec. Otherwise, in recoiling from the π -particle, it would move away from the original point of decay, and the two charged particles into which it became transformed would originate from a point separated from the beginning of the track of the π^- -particle. It follows that we cannot identify such a postulated unstable neutral particle with that for which evidence is provided in the experiments of Rochester and Butler. [中文](#)

Finally, we have considered the possible relations of the present results to the particles of mass approximately $800 m_e$ referred to as τ -mesons, evidence for which has been recently reported by Bradt and Peters². It is a remarkable feature of their experiments that their τ -mesons give rise to no recorded secondary particles at the end of their range. It appears to be possible that these particles also decay with the emission of three fast mesons, but that the transmutation usually takes place with a more equal partition of kinetic energy than in the case we have observed. It would then follow that in the Ilford C2 emulsion the disintegration products would commonly escape observation. If this view is correct, we must regard the event we have observed as representing a rare example of a common mode of decay of these mesons; an example which, by chance, has allowed a detailed analysis to be carried out. If so, the τ -meson of Bradt and Peters, when recorded by electron-sensitive emulsions, should show the tracks of three particles, of low specific ionization, and of which the directions of motion are co-planar. [中文](#)

We have pleasure in thanking Prof. von Muralt and members of the staff of the Jungfrauoch Forschungsstation for hospitality and assistance in obtaining the exposures; Dr. E. R. Davies and Dr. W. E. Berriman, of Messrs. Kodak, Ltd., for special photographic plates; Miss C. Dilworth and Dr. G. P. S. Occhialini for advice on development; Mr. W. O. Lock and Mr. J. H. Davies for assistance in making observations

on the scattering of particles in the emulsion; and to the team of microscope observers of this Laboratory. We are indebted to Prof. N. F. Mott and other colleagues for a number of discussions on the processes associated with the capture of negative mesons by nuclei.

[中文](#)

Note added in proof. Since completing this article, we have been informed by Dr. Peters that, in Ilford C2 emulsions exposed at 90,000 feet, he and Dr. Bradt have observed three events with the following characteristics. A particle, which they judge to be similar in mass to their τ -mesons, appears to come to rest and to lead to the emission of a particle of smaller mass, which, at the end of its range, produces a nuclear disintegration. The ranges of the secondary particles, in the three cases, are 20, 25 and 45 μ , respectively. The authors were not aware of our results when they suggested to us that their observations may correspond to the spontaneous decay of heavy mesons. According to their description, these events are precisely similar to those we should expect to observe in C2 emulsions as a result of the spontaneous decay of heavy particles of the type we have postulated; for any particles of low specific ionization will not be recorded by the Ilford plates. The observations of Peters and Bradt appear, therefore, to give further support for the assumption that the present observations are not due to a chance juxtaposition of tracks; and they suggest that it will be possible, in the near future, to find similar examples suitable for making a detailed analysis. [中文](#)

(163, 82-87; 1949)

R. Brown, U. Camerini, P. H. Fowler, H. Muirhead and C. F. Powell: H. H. Wills Physical Laboratory, University of Bristol.

D. M. Ritson: Clarendon Laboratory, Oxford.

References:

1. Berriman, *Nature*, **162**, 992 (1948).
2. Leprince-Ringuet, C.R., **226**, 1897 (1948). Rochester and Butler, *Nature*, **160**, 855

- (1947). Bradt and Peters, Report to the Bristol Symposium, 1948 (in the press). Alichanian. Alichanov and Weissenberg, *J. Exp. and Theoret. Phys., U.S.S.R.*, **18**, 301 (1948); and other references.
3. Camerini, Muirhead, Powell and Ritson, *Nature*, **162**, 433 (1948).
 4. Goldschmidt-Clermont, King, Muirhead and Ritson, *Proc. Phys. Soc.*, **61**, 138 (1948).
 5. Lattes, Occhialini and Powell, *Proc. Phys. Soc.*, **61**, 173 (1948).
 6. Serber, Report of Solvay Conference for 1948.
 7. Dilworth, Occhialini and Payne, *Nature*, **162**, 102 (1948).
 8. Occhialini and Powell, *Nature*, **162**, 168 (1948).
 9. Halpern and Hall, *Phys. Rev.*, **73**, 477 (1948).
 10. Livingston and Bethe, *Rev. Mod. Phys.*, **9**, 263 (1937).
 11. Camerini and Lattes (private communication); see also Powell and Occhialini, "Nuclear Physics in Photographs", 112 (Oxford, 1947).

* For the following reasons, the limits of error quoted above, in the determination of m_π/m_μ by observations on scattering, are less than those given in ref. 4. Previously, values for the mass of the different types of mesons, classified phenomenologically, were given separately. It is now known, however, that at least the majority of the σ -mesons are π^- -particles; and the ρ^- -mesons, μ^+ - and μ^- -particles. The different results can therefore be combined to give a value for m_π/m_μ with a greater statistical weight.

在宇宙辐射下曝光的电子敏感底片的观测

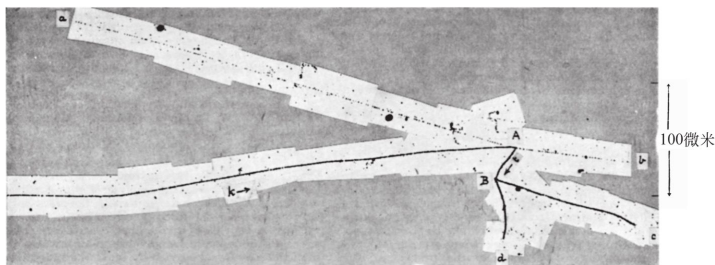
布朗等

最近新发现了一种大约具有1,000倍电子质量的粒子，受到其实验证据的启发，物理学家塞西尔·鲍威尔和同事们在本文中报道了高海拔云室宇宙射线实验：来自太空的高能粒子。他们分析了一个具有单位电荷的“ k 粒子”（后来称为 K 介子）的径迹，这个粒子进入云室后衰变为另外两个粒子。通过计算照相颗粒他们估算了这个 k 粒子的质量，结果发现其质量大约是电子质量的1,080倍。他们把这种衰变解释为一个产生两个 π 介子的过程。这些结果促使人们在之后十年内有了新的发现，即包含弱核力相互作用并不遵守镜面对称。

[英文](#)

在检查少女峰上曝光的电子敏感底片时，我们最初的重要发现之一就是如图8中显微照片的拼嵌图所表示的记录。图中存在两个中心A和B，带电粒子的径迹从这两点开始分裂，并且以常见的径迹 t 相连接。由于曝光的时间很短，并且仅有少量的蜕变反映在底片上，因此观测结果中对应于无关事件径迹偶然交叉重叠的可能性是非常小的，仅为 1×10^{-7} 量级，因此我们可以将这种重要的可能性合理地排除。后面我们将会给出进一步支持上述假设的观测结果。

[英文](#)



观测者：范德梅伟

图8 英文

对径迹 k 的检验表明，产生它的粒子到达蜕变中心 A 的附近。该粒子在乳胶中的射程超过3,000微米，在接近 A 的过程中，径迹的颗粒密度逐渐增加。在 A 附近，其颗粒密度与同在该底片上记录的电荷为 e 的粒子接近射程终端处的颗粒密度无法区分。 英文

观测发现库仑散射造成了径迹的小角度偏离，这支持了基于颗粒计数得到的关于粒子运动方向的证据。这些偏离在靠近 A 时出现得最为频繁，而散射在远离 A 的各点处比较不明显。 英文

根据这些观测我们有理由认为，粒子 k 向 A 点靠近；它携带着基本电子电荷，并在 A 点附近达到或接近其射程的终端。因此我们假设，粒子 k 引发了一连串由 A 和 B 的辐射径迹所代表的事件。由此可知，该粒子产生了源自 A 点并在 B 点产生蜕变的径迹 t 。为了分析该事件，我们首先尝试了对粒子 k 的质量进行确定。 英文

根据颗粒计数所做的质量测定

约在一年前，本实验室采用颗粒计数的方法^[5]以及研究粒子通过乳胶时小角度散射的方法^[4]，进行了测定 π 介子和 μ 介子（编者注：现在粒子物理认为“ μ 介子”不是介子，而是一种轻子，因此正确的称谓应为“ μ 子”。考虑到历史原因，文中仍保留“ μ 介子”的译法。）的质量比 m_π/m_μ 的实验。用这两类方法得到的结果分别为 $m_\pi/m_\mu = 1.65 \pm 0.11$ 和 $m_\pi/m_\mu = 1.35 \pm 0.10^*$ 。最近在伯克利进行的实验^[6]表明，其真值为 1.33 ± 0.02 ，这个结果使人们对颗粒计数方法的可靠性产生了严重的怀疑。但是考虑到该方法的优点，以及据此得到的一些重要结论，我们进行了一些实验来确定在何种条件下才能获得可靠的结果。 英文

在首次实验中^[5]，两个最为严重的实验难点来自潜影的褪色和显像度随深度的变化。若要对同一对 π 介子和 μ 介子径迹的颗粒数密度进行对比，就必须研究同时形成的径迹。然而这样一来，可以用于测量的 π 介子的径迹大多小于400微米。在后续的实验中，通过运用短期曝光的方法获得了更多良好条件，这使得褪色效应可以被忽略；与此同时，还采用了迪尔沃思、奥恰利尼和佩恩^[7]所使用的冲洗底片的方法，这种方法获得了与深度几乎一致的显像度。 [英文](#)

用上述方法得到的底片来比较不相关粒子径迹的颗粒密度是合理的。此外，现在知道，产生“星”点的介子中至少多数甚至可能全部是 π^- 粒子^[6,8]；而大多数 ρ 介子是 μ^+ 粒子和 μ^- 粒子。因此在测定 m_π 和 m_μ 的实验中，我们对长度大于1,000微米的 π^+ 和 π^- 、 μ^+ 和 μ^- 粒子的径迹进行了测量，并将其与用类似方法对质子径迹的测量结果做了比较。在上述条件下，我们得出 $m_\pi/m_\mu = 1.33 \pm 0.05$ 。观测的详细计算将另行发表；考虑到本文的目的，这里只需指出该结果与用其他方法获得的结果非常一致就足够了。由此我们认为，在新的条件下，用伊尔福C2乳胶能够获得可靠的信息。 [英文](#)

我们已经知道，目前实验中所用的新柯达乳胶已可以同时满足均匀显像和不变色的条件，因此我们试图用类似方法并使用伊尔福胶片对粒子的质量进行测量。图9显示了在同一胶片中四个质子和四个 μ 粒子的径迹的观测结果。在图中，用径迹中单位长度的颗粒数对不同残余射程值作图；同一类型径迹的平均值用粗线表示。两类粒子的质量比可通过比较颗粒密度相同时所对应的残余射程值导出。由此得到的结果为 $m_\mu = 220 \pm 20 m_e$ 。 [英文](#)

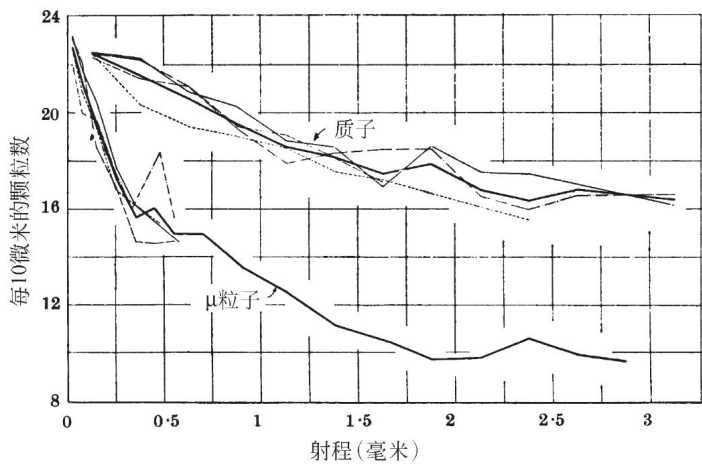


图9 英文

用类似的方法，我们已估算了粒子k的质量值，测量结果如图10所示。这个图给出了四个μ介子和四个质子的径迹中的颗粒密度的平均值，同时也给出了粒子k的颗粒密度。上述所有径迹均在同一张底片中获得。

英文

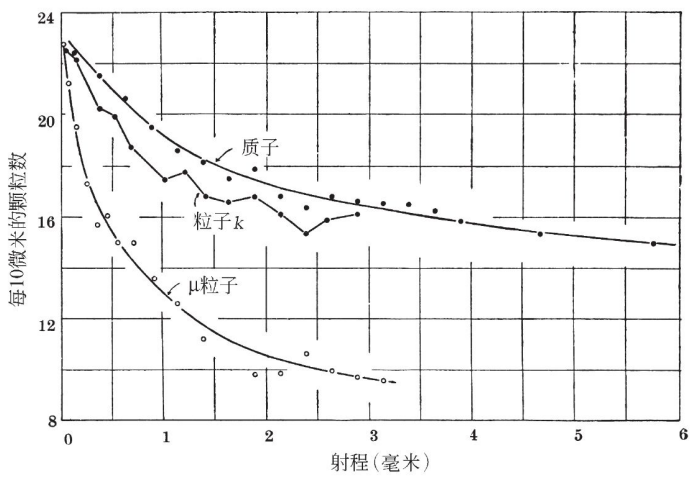


图10 英文

将粒子k径迹中的颗粒密度与质子平均曲线进行对比，表1给出了比较结果以及由此测定的k粒子的质量值。这些值都是独立的，平均值是 $m_k = 1,080 \pm 160 m_{e0}$ 。

英文

表1. 利用颗粒计数测得的质子质量与粒子k质量的比值 m_p/m_k

各自独立的值							
m_p/m_k	1.77	1.88	1.49	1.64	2.17	1.79	1.32
	1.71	1.66	1.27	1.69	2.13	1.55	
平均值: 1.70 ; $m_k = 1,080 \pm 160 m_e$							

英文

上述给出的误差极限由下述方式导出：我们已对四个单独质子的径迹中的颗粒密度与它们的径迹颗粒密度的平均曲线（见图9）进行了比较，并由此得到了每个粒子表观质量的若干独立值。根据这些值的分布，我们可以计算出在依据每个单独径迹测定质量的过程中所产生的“或然误差”，并将其表示为粒子表观质量的百分比。然后我们假设计算出的粒子 k 的质量具有相同的“或然”百分比误差。

英文

我们也用最近介绍的方法^[4]，即通过研究粒子的小角度散射确定了质量 m_k ，由此得到的结果是 $m_k = 1,800 \pm 400 m_e$ 。如果粒子质量的真值是 $1,080 m_e$ ，通过散射观测得到的值等于或大于 $1,800 m_e$ 的概率是 $1/4$ 。由于散射实验的观测有较大的统计涨落，因此我们给颗粒计数的测量以更大的权重。根据这些观测，似乎可以肯定， m_k 的真值位于 $700 m_e$ 和 $1,800 m_e$ 之间，我们认为它极可能远小于质子的质量。因此，在某一特定的残余射程值处，径迹 k 中每一个表示颗粒密度的点，都位于四个质子中相应的点之下。

英文

“B”蜕变

由点 B 发射的两个粒子的径迹 c 和 d 具有质子或较重粒子的特性，我们认为这源自于粒子 t 产生的蜕变。该粒子在通过乳胶时频繁地散射，因此速度很低；这个现象与其在 B 点达到射程终点的假设是一致的。

英文

目前已知能够产生具有星点 B 特征的蜕变的慢带电粒子只有 π^- 粒子^[6,8]。因此我们假定，在点 A 产生了质量为 $286 m_e$ 的负介子，在达到其射程终点时产生 B 蜕变。

英文

“A”嬗变

为了解释 A 嬗变，我们首先对发射粒子的径迹做了详细的检查。在

径迹 a 和 b 中，前者的径迹在乳胶中的长度大于2,000微米，并在表面终止，而径迹 b 的长度是116微米且在玻璃中终止。两个径迹的颗粒密度在统计涨落所确定的极限之内相等。在长径迹 a 中，平均颗粒密度是每100微米49.0个颗粒，该密度是电荷为 e 的粒子最小电离特征值的2.17倍。除非我们允许存在电荷的分数值，否则我们必然会得出，产生径迹 a 和 b 的粒子的带电量均为 e 的量级。

英文

为了测定产生径迹 a 和 b 的粒子能量的可能值，我们假定乳胶的原子组分与伊尔福C2胶片相同，根据哈尔彭和霍尔的公式^[9]计算了电荷为 e 的粒子的比电离值随能量的变化。这个公式是布洛赫公式^[10]的修正形式；该公式适用于在固体介质中运动的粒子，并给出了与低能粒子的实验非常符合的结果。结果示于图11中，将比电离值作为量 E/m 的函数绘图， E 和 m 分别为粒子的能量和质量，两个量均以兆电子伏为单位测量。根据图11，假定粒子是质子、 π 介子、 μ 介子或电子，我们确定了对应于径迹中观测到的颗粒密度的粒子 a 、 b 能量的可能值。所得到的结果列于表2中。

英文

表2. 基于有关粒子质量的各类假设，根据观测颗粒密度和散射导出的产生径迹 a 的粒子的能量和动量值

假设的粒子	质子	π 介子	μ 介子	电子
能量 (兆电子伏) $\left\{ \begin{array}{l} (a) \text{ 在最小电离作用之下} \\ (b) \text{ 在最小电离作用之上} \end{array} \right.$	235 ± 95	37 ± 13	27 ± 11	0.13 ± 0.05 $> 1,000$
动量 (兆电子伏 / 光速) $\left\{ \begin{array}{l} (a) \text{ 在最小电离作用之下} \\ (b) \text{ 在最小电离作用之上} \\ (c) \text{ 根据散射观测} \\ (d) \text{ 根据动量平衡} \end{array} \right.$	700 ± 160 245 ± 40 98 ± 5	109 ± 22 113 ± 18 98 ± 5	80 ± 15 100 ± 16 98 ± 5	0.4 ± 0.1 $> 1,000$ 68 ± 11 98 ± 5

英文

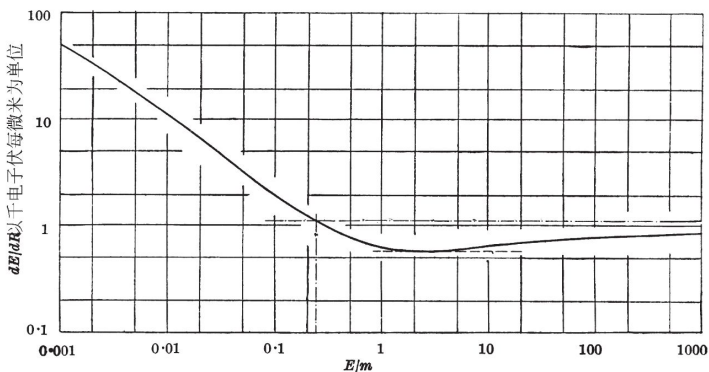


图11．电荷为 $|e|$ 的粒子能量损失的速率随 E/m 变化的函数。其中 E 是动能， m 是粒子质量，两个量的测量单位都是兆电子伏。 [英文](#)

粒子 k 在 A 点产生嬗变有两种可能的解释。我们可以假定，粒子或被核俘获，或产生自发衰变。从粒子质量的测量值来看，根据质量和能量守恒的观点，可能的情况是它在乳胶中射程的终点处被核俘获，并导致两个高能质子和一个 π^- 粒子的发射。然而几乎同样确定的是，如此大量的能量在核中释放将导致很多核子的“蒸发”，这个过程在对宇宙辐射曝光的底片中很常见；还可以基本确定的是两个高能质子将是“多股”星仅有的两个组分。（可以注意到，我们不可以假定粒子 k 是被存在于凝胶体中的某个稀有的重氢核所俘获。在这种相互作用中，两个初始粒子电荷的代数和是 0 或 $2e$ ，而产生的粒子的电荷代数和是 e 或 $3e$ 。）对于径迹 a 和 b 是由质子或带电荷 e 的较重核产生的这一假说，稍后我们将介绍其他一些反对意见。 [英文](#)

根据上述考虑，如果我们要用已确定存在的粒子来描述嬗变，那么我们必须将径迹 a 和 b 认为是由电子、 μ 介子或 π 介子这三者之一所产生的。如果是电子，则我们必须假设电子的能量大于相应的最小电离能，即大于 $1,000$ 兆电子伏；对应于观测到的较低的电离入射能量 300 千电子伏，粒子在乳胶中仅有约 100 微米的射程，并且会被频繁地散射。因此认为粒子 a 和 b 是电子的假设与能量守恒不相符，可以被排除。我们只能在剩下的 π 介子或 μ 介子中择一作为产生径迹的粒子。 [英文](#)

如果粒子 a 和 b 是介子，那么为了使质能守恒，我们必须假定在 μ 介子或 π 介子的情况下（见图11），其动能分别为 27 兆电子伏和 37 兆电子伏。如果假设粒子的发射是由于核内释放了相应于粒子 k 静止质量的能

量，那么无论是上述哪种介子，观测结果都很难与该假设相一致。因此，我们只能尝试用这个粒子的自发衰变来对观测结果进行解释了。

英文

k 粒子自发衰变的假定

在确定A嬗变是否对应于粒子 k 的自发衰变时，我们需要知道三个射出粒子的相对运动方向。为此必须确定乳胶的收缩，即在曝光时乳胶的厚度与经过显影、定影和烘干后的乳胶的厚度比值 S 。我们已经通过检验在不可控制的放射性污染下乳胶中产生的 α 粒子的径迹测量了这个量。在这类“星”中，可以确定其中一些情况是由放射性钍的天然原子产生的，一个钍 C' 发射一个 α 粒子。通过测定乳胶表面上相应径迹投影的长度以及其“下陷”的表观角度，已测得了乳胶的收缩。由此获得的“收缩”值为 $S = 2.7 \pm 0.1$ 。知道了 S 的值，那么通过观测粒子“下陷”的表观角度以及由乳胶表面确定的平面投影方向，便可以测定乳胶被处理前其中的径迹的原始取向，在较好的情况下，精度可达 1° 量级。采用这些方法，获得的三个粒子 a 、 b 、 t 运动的原始方向是共面的。任何一个粒子的运动方向与另两个粒子所确定的平面之间的偏离小于 4° 。在这项测定中的误差主要来源于径迹 t 是短程的，产生它的粒子是低速的并被频繁地散射。

英文

共面的粒子运动方向之间的角度值示于图12中。根据观测到的共面性可以合理地得出以下假设：三个粒子来自粒子 k 在乳胶的射程终端的自发衰变，并且它们是蜕变仅有的产物，整个过程没有中性粒子发射（中性粒子无法观测）。由此，必然会得出三个粒子动量的矢量和等于零的结论。

英文

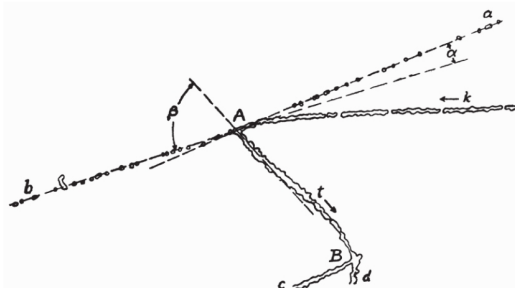


图12. 用投影显微镜作的图8中示出的事件的复制图。在三个径迹 a 、 b 、 t 的共面中测得的实际

角 α 和 β 分别是： $\angle\alpha = 9.8^\circ$ ， $\angle\beta = 76.6^\circ$ 。[英文](#)

如果我们将径迹*t*归因于 π^- 粒子是正确的，则根据观测到45微米的射程可得，发射的动能是1.04兆电子伏。该粒子相应的动量值是17.5兆电子伏/光速。根据观测到的运动方向，可得产生径迹*a*和*b*的粒子的动量分别为 98 ± 5 兆电子伏/光速和 104 ± 5 兆电子伏/光速。这些值将与表2中列出的根据观测的径迹中颗粒密度而导出的相应的电子或介子的数值相比较。我们已看到表2中列出的两个粒子的动量值，如果假定它们是电子，则这些值显然已大出很多倍。因此如果假定径迹*a*和*b*是由电子或质子产生的，则与动量平衡存在很大的偏差。而且无论粒子是电子还是质子（见表2），根据粒子观测到的散射而导出的动量值与从颗粒密度得出的值也是不一致的。[英文](#)

然而，介子的数值之间的一致性是最为突出的，这有力地支持了粒子*k*的自发衰变的假设。如果结果是偶然的，那么须同时具备以下几个不相关的特征才能得到与估算的动量值吻合很好的情况，这些特征包括：在同一平面中粒子的径迹和运动方向的共面性、粒子*t*的射程以及产生径迹*a*和*b*的粒子电离比值，而这种情况是非常罕见的。[英文](#)

假设粒子*k*发生自发衰变，则无论产生的粒子是 μ 介子还是 π 介子，用三类不同方法测定的产生径迹*a*和*b*的粒子的动量值，在测量误差允许的范围内都是一致的。我们可以通过计算两种不同假设下的粒子*k*的静止质量来进行进一步的测试，结果列于表3中。[英文](#)

表3. 对两类假定的衰变方式，基于总的质量和能量释放对粒子*k*的质量估算

(i) $k \rightarrow \pi^- + \pi + \pi$			
	径迹 “a”	径迹 “b”	径迹 “t”
粒子	π	π	π^-
静止质量 (m_r)	286	286	286
能量 (m_e)	61	64	2
总质量 = $m_k = 985\ m_e$			
(ii) $k \rightarrow \pi^- + \mu + \mu$			
粒子	μ	μ	π^-
静止质量 (m_r)	212	212	286
能量 (m_e)	76	81	2
总质量 = $m_k = 869\ m_e$			

在计算产生径迹*a*和*b*的粒子的能量时，假设产生径迹*t*的是一个 π^- 粒子，动量为17.5兆电子伏/光速；已知三个出射粒子的相对运动方向，则另两个粒子的动量可确定，因此可以得出对应于任一假定质量的能量值。[英文](#)

由表3可见，两个 μ 介子的假设对应于粒子 k 的静止质量为 $869\ m_e$ ；两个 π 介子对应 $985\ m_e$ 。不同粒子，即一个 μ 介子和一个 π 介子的假设，给出的中间值近似为 $925\ m_e$ 。考虑到直接测定 m_k 时产生的误差，上述结果无法给出决定性判据。

英文

如果用已确定存在的粒子来解释嬗变，考虑到产生径迹 a 和 b 的粒子所具有的特征，那么就只剩下四种可能性，结果列于表4中。

英文

表4. 根据产生径迹 a 和 b 的粒子的特征而对粒子种类做出的各类假设，并对径迹 b 的颗粒密度的观测值与计算值进行了比较

	径迹的长度 (微米)	颗粒数	颗粒密度	假设的粒子			
				1	2	3	4
径迹 a	2,100	1,025	49 ± 1.5	π	μ	π	μ
径迹 b	116	59	51 ± 6	π	μ	μ	π
径迹 b 的颗粒密度的计算值				45	45	34	64

颗粒密度的值指每100微米的颗粒数。

英文

由于下述的理由，表4中第三种情况是最不可能的。因为如果径迹 a 是一个 π 介子形成的，我们可以计算出径迹 b 中预期的动量值和颗粒密度。由此我们获得的颗粒密度是每微米34个颗粒，而不是观测到的 51.0 ± 6.0 。反之，对于第四种情况，如果 a 是一个 μ 介子，计算的径迹 b 的颗粒密度为64，这个值与观测量之间的差别仅为相应标准偏差的2倍。观测的颗粒密度与在假定两个粒子是同类型的情况下计算得到的颗粒密度值吻合得最好。

英文

产生径迹 a 的粒子的散射观测更符合 π 介子的假设，而不是 μ 介子（见表2）；但结果也是非决定性的。我们可以将这个证据与用颗粒密度的质量测定所提供的证据综合在一起，认为这是对产生的三个粒子都是 π 介子的观点的支持；但一个 π 介子和两个 μ 介子的组合或两个 π 介子和一个 μ 介子的组合的可能性也不能排除。

英文

无关事件的机遇并置

按照前几节的分析，我们现在回到最初的假设，即事件并不是径迹偶然的交叉重叠。粒子 k 质量测定的准确度不允许我们排除其质量大如质子的可能性，虽然颗粒计数的观测结果证明这种情况不可能。假设质

子与产生其他径迹的粒子无关，在A处到达射程终点。即使采用这个假设，事件仍然很难用传统观点来解释。本实验室^[8]观测到许多从星发射出 π^- 粒子的例子，但在目前的例子中，发射两个高能质子，并且不伴随产生慢质子和 α 粒子，这种核相互作用的情况是否存在仍然需要进一步证实。而如果我们假设产生径迹a或b的粒子靠近A，并产生嬗变，也会遇到类似的困难。 [英文](#)

另一种可能性是，如果从星B散射的径迹c和d代表一个无关的蜕变（例如是由 γ 射线所导致的），那么我们可以假定径迹t是质子的径迹。我们可以将困难与星A独有的特点相联系，并必须假定它是由低速带电粒子产生的，而这样假设遇到的困难已在以前的段落中进行了讨论。这些分析给原始假设以进一步的支持，拼嵌图中所有的径迹代表了一个不断延续发生的相关过程。 [英文](#)

目前结果与其他观测的关系

如果带有基本电子电荷的粒子发生自发衰变，根据电荷守恒定律可知，其发射的电荷为e的粒子的数量应为奇数。根据这个观点，原始粒子的电荷符号不是正号就是负号。如果产生径迹a和b的粒子的电荷符号相反，则原始的k粒子带负电。仅有的另一种可能是，它们两者都带正电荷，在这种情况下，k粒子也是正的。因此可能的情况是，我们的观测对应于质量近似为 $900 m_e$ 的带正电粒子的衰变模式，而由勒普兰斯-兰盖^[2]的观测则表明了相应的负电粒子的情况，即核俘获产生“星”并发射 π^- 粒子。 [英文](#)

罗切斯特和布特勒^[2]已发表了一张膨胀室的照片，它记录的可能是质量近似为 $900 m_e$ 的中性粒子自发衰变形成了一对电荷相反的静止质量近似为 $300 m_e$ 的粒子。因此我们认为，该结果反映的衰变过程可能分为两个步骤：一个低能 π^- 粒子的发射和随后产生的中性粒子的自发衰变。然而，根据这个观点，必须假设，中性粒子的寿命为 10^{-14} 秒的量级。否则中性粒子在 π^- 粒子的反冲中，可能会离开衰变的原点，因此嬗变产生的两个带电粒子将从与 π^- 粒子径迹的起点不同的点起源。因此，根据罗切斯特和布特勒的实验中提供的证据，我们并不能确认存在这类假定的不稳定的中性粒子。 [英文](#)

最后，我们考虑了目前的结果与质量近似为 $800\ m_e$ 的 τ 介子（编者注：现在粒子物理认为“ τ 介子”不是介子，而是一种轻子，因此正确的称谓是 τ 子。考虑到历史原因，文中仍保留“ τ 介子”的译法。）的可能关系，关于 τ 介子的证据最近已由布拉特和彼得斯^[2]做了报道。他们实验的一个显著特征就是，在 τ 介子的射程内没有记录到次级粒子。因此很可能是 τ 介子在衰变的过程中伴随三个快介子的发射，但是这种嬗变通常发生在比我们所观测到的动能更加均分的情况下。由此可知，在伊尔福C2乳胶中，蜕变产物通常会观测不到。如果这个观点是正确的，我们必须认为我们已观测到的事件是这些介子衰变的一般模式中的一个稀有例子，一个碰巧允许我们进行详细分析的例子。如果是这样，那么布拉特和彼得斯的 τ 介子在被用电子敏感的乳胶记录时，应该会显示低电离比值的三个粒子的径迹，且运动方向是共面的。 英文

诚挚感谢冯·穆拉尔特教授和少女峰研究站的工作人员，感谢他们的热情和在曝光过程中对我们的帮助；感谢柯达公司的戴维斯博士和贝里曼博士提供的特殊的照相底片；感谢迪尔沃斯女士和奥恰利尼博士关于显影的建议；感谢洛克先生和戴维斯先生在观察感光乳液中的粒子散射时所给予的协助；感谢本实验室的显微镜观测小组。此外，我们还特别感谢莫脱教授和其他同事关于核子捕捉负电介子的过程而进行的大量讨论。 英文

附加说明：本文完成以后，彼得斯博士又给我们提供了一些新的信息：将伊尔福C2乳胶置于海拔90,000英尺处曝光，他和布拉特博士观测到三个具有下述特性的事件。一个质量与他们的 τ 介子相当的粒子在其射程的终端趋于静止，并产生一个质量更小的粒子，该粒子在其射程的终端激发了一个核蜕变。在三类情况下，次级粒子的射程分别为20微米、25微米和45微米。当他们向我们提出他们的观测可能与重介子的自发衰变相符合时，作者并不知道我们的结果。按照他们的描述，这些事件非常类似于我们预期在C2乳胶中观测的我们所假设的这类重粒子的自发衰变结果；伊尔福C2胶片不能记录任何低电离比值的粒子。因此，彼得斯和布拉特的观测结果进一步支持了下述假设，即目前的观测并不是偶然的径迹交叉重叠；他们表示在不久的将来有可能发现适合做详细分析的类似实例。 英文

* 基于以下理由，上文所引用的由散射观测给出的 m_{π}/m_{μ} 值的误差极限要比参考文献4中的小。以前，基于现象分类的不同介子的质量是分别给出的。然而现在已知，至少 σ 介子中大部分是 π^- 粒子， ρ 介子中大部分是 μ^+ 和 μ^- 粒子，将不同的结果综合起来可得一个更大统计权重下的 m_{π}/m_{μ} 数值。

Correlation between Photons in Two Coherent Beams of Light

R. Hanbury-Brown and R. Q. Twiss

In classical interferometry, phase differences between two interacting light beams probe differences in their travelled paths. In the early 1950s, Robert Hanbury-Brown and Richard Twiss proposed that a new means of interferometry, using only the intensity (not the phase) of light, could be used to estimate the angular size of distant stars. Here they report a laboratory demonstration of the effect. The result illustrated the quantum “bunching” of photons—the tendency for photons in two separate, coherent beams to arrive together at two detectors. The Hanbury-Brown Twiss effect now refers generally to any correlation or anti-correlation in the intensities of signals measured by two detectors from a beam of particles. Intensity interferometry has become an important technique in nuclear and particle physics. [中文](#)

IN an earlier paper¹, we have described a new type of interferometer which has been used to measure the angular diameter of radio stars². In this instrument the signals from two aerials A_1 and A_2 (Fig. 1a) are detected independently and the correlation between the low-frequency outputs of the detectors is recorded. The relative phases of the two radio signals are therefore lost, and only the correlation in their intensity fluctuations is measured; so that the principle differs

radically from that of the familiar Michelson interferometer where the signals are combined before detection and where their relative phase must be preserved. 中文

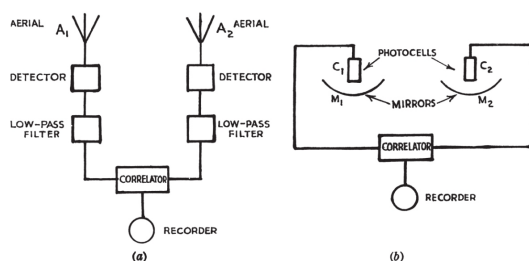


Fig. 1. A new type of radio interferometer (a), together with its analogue (b) at optical wavelengths 中文

This new system was developed for use with very long base-lines, and experimentally it has proved to be largely free of the effects of ionospheric scintillation². These advantages led us to suggest¹ that the principle might be applied to the measurement of the angular diameter of visual stars. Thus one could replace the two aerials by two mirrors M_1 , M_2 (Fig. 1b) and the radio-frequency detectors by photoelectric cells C_1 , C_2 , and measure, as a function of the separation of the mirrors, the correlation between the fluctuations in the currents from the cells when illuminated by a star. 中文

It is, of course, essential to the operation of such a system that the time of arrival of photons at the two photocathodes should be correlated when the light beams incident upon the two mirrors are coherent. However, so far as we know, this fundamental effect has never been directly observed with light, and indeed its very existence has been questioned. Furthermore, it was by no means certain that the correlation would be fully preserved in the process of photoelectric emission. For these reasons a laboratory experiment was carried out as described below. 中文

The apparatus is shown in outline in Fig. 2. A light source was formed by a small rectangular aperture, 0.13 mm. $\times$ 0.15 mm. in cross-

section, on which the image of a high-pressure mercury arc was focused. The 4,358 Å. line was isolated by a system of filters, and the beam was divided by the half-silvered mirror M to illuminate the cathodes of the photomultipliers C_1 , C_2 . The two cathodes were at a distance of 2.65 m. from the source and their areas were limited by identical rectangular apertures O_1 , O_2 , 9.0 mm. $\times$ 8.5 mm. in cross-section. (It can be shown that for this type of instrument the two cathodes need not be located at precisely equal distances from the source. In the present case their distances were adjusted to be roughly equal to an accuracy of about 1 cm.) In order that the degree of coherence of the two light beams might be varied at will, the photomultiplier C_1 , was mounted on a horizontal slide which could be traversed normal to the incident light. The two cathode apertures, as viewed from the source, could thus be superimposed or separated by any amount up to about three times their own width. The fluctuations in the output currents from the photomultipliers were amplified over the band 3–27 Mc./s. and multiplied together in a linear mixer. The average value of the product, which was recorded on the revolution counter of an integrating motor, gave a measure of the correlation in the fluctuations. To obtain a significant result it was necessary to integrate for periods of the order of one hour, so very great care had to be taken in the design of the electronic equipment to eliminate the effects of drift, of interference and of amplifier noise.

中文

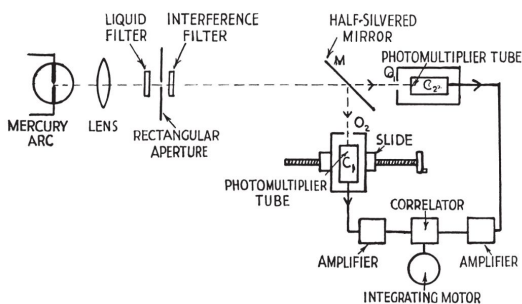


Fig. 2. Simplified diagram of the apparatus

中文

Assuming that the probability of emission of a photoelectron is

proportional to the square of the amplitude of the incident light, one can use classical electromagnetic wave theory to calculate the correlation between the fluctuations in the current from the two cathodes. On this assumption it can be shown that, with the two cathodes superimposed, the correlation $S(0)$ is given by:

$$S(0) = A \cdot T \cdot b_v f\left(\frac{a_1 \theta_1 \pi}{\lambda_0}\right) \cdot f\left(\frac{a_2 \theta_2 \pi}{\lambda_0}\right) \int \alpha^2(\nu) \cdot n_0^2(\nu) \cdot d\nu \quad (1)$$

It can also be shown that the associated root-mean-square fluctuations N are given by:

$$N = A \cdot T \cdot \frac{2m}{m-1} \cdot b_v (b_v T)^{-\frac{1}{2}} \int \alpha(\nu) \cdot n_0(\nu) \cdot d\nu \quad (2)$$

where A is a constant of proportionality depending on the amplifier gain, etc.; T is the time of observation; $\alpha(\nu)$ is the quantum efficiency of the photocathodes at a frequency ν ; $n_0(\nu)$ is the number of quanta incident on a photocathode per second, per cycle bandwidth; b_v is the bandwidth of the amplifiers; $m/(m-1)$ is the familiar excess noise introduced by secondary multiplication; a_1, a_2 are the horizontal and vertical dimensions of the photocathode apertures; θ_1, θ_2 are the angular dimensions of the source as viewed from the photocathodes; and λ_0 is the mean wave-length of the light. The integrals are taken over the complete optical spectrum and the phototubes are assumed to

be identical. The factor $f\left(\frac{a\theta\pi}{\lambda_0}\right)$ is determined by the dimensionless parameter η defined by

$$\eta = a\theta/\lambda_0 \quad (3)$$

which is a measure of the degree to which the light is coherent over a photocathode. When $\eta \ll 1$, as for a point source, $f(\eta)$ is effectively unity; however, in the laboratory experiment it proved convenient to make η_1, η_2 of the order of unity in order to increase the light incident on the cathodes and thereby improve the ratio of signal to noise. The corresponding values of $f(\eta_1), f(\eta_2)$ were 0.62 and 0.69 respectively.

When the centres of the cathodes, as viewed from the source, are displaced horizontally by a distance d , the theoretical value of the correlation decreases in a manner dependent upon the dimensionless parameters, η_1 and d/a_1 . In the simple case where $\eta_1 \ll 1$, which would apply to an experiment on a visual star, it can be shown that $S(d)$, the correlation as a function of d , is proportional to the square of the Fourier transform of the intensity distribution across the equivalent line source. However, when $\eta \geq 1$, as in the present experiment, the correlation is determined effectively by the apparent overlap of the cathodes and does not depend critically on the actual width of the source. For this reason no attempt was made in the present experiment to measure the apparent angular size of the source.

中文

The initial observations were taken with the photocathodes effectively superimposed ($d = 0$) and with varying intensities of illumination. In all cases a positive correlation was observed which completely disappeared, as expected, when the separation of the photocathodes was large. In these first experiments the quantum efficiency of the photocathodes was too low to give a satisfactory ratio of signal to noise. However, when an improved type of photomultiplier became available with an appreciably higher quantum efficiency, it was possible to make a quantitative test of the theory.

中文

A set of four runs, each of 90 min. duration, was made with the cathodes superimposed ($d = 0$), the counter readings being recorded at 5-min. intervals. From these readings an estimate was made of N_e , the root mean square deviation in the final reading $S(0)$ of the counter, and the observed values of $S_e(0)/N_e$ are shown in column 2 of Table 1. The results are given as a ratio in order to eliminate the factor A in equations (1) and (2), which is affected by changes in the gain of the equipment. For each run the factor

$$\frac{m-1}{m} \int \alpha^2(v) n_0^2(v) dv / \int \alpha(v) n_0(v) dv$$

was determined from measurements of the spectrum of the incident light and of the d.c. current, gain and output noise of the photomultipliers; the corresponding theoretical values of $S(0)/N$ are shown in the second column of Table 1. In a typical case, the photomultiplier gain was 3×10^5 , the output current was 140 μ amp., the quantum efficiency $\alpha(v_0)$ was of the order of 15 percent and $n_0(v_0)$ was of the order of 3×10^{-3} . After each run a comparison run was taken with the centres of the photocathodes, as viewed from the source, separated by twice their width ($d = 2a$), in which position the theoretical correlation is virtually zero. The ratio of $S_e(d)$, the counter reading after 90 minutes, to N_e , the root mean square deviation, is shown in the third column of Table 1. 中文

Table 1. Comparison between the Theoretical and Experimental Values of the Correlation

Cathodes superimposed ($d = 0$)		Cathodes separated ($d = 2a = 1.8$ cm.)	
Experimental ratio of correlation to r.m.s. deviation $S_e(0)/N_e$	Theoretical ratio of correlation to r.m.s. deviation $S(0)/N$	Experimental ratio of correlation to r.m.s. deviation $S_e(d)/N_e$	Theoretical ratio of correlation to r.m.s. deviation $S(d)/N$
1 +7.4	+8.4	-0.4	~ 0
2 +6.6	+8.0	+0.5	~ 0
3 +7.6	+8.4	+1.7	~ 0
4 +4.2	+5.2	-0.3	~ 0

中文

The results shown in Table 1 confirm that correlation is observed when the cathodes are superimposed but not when they are widely separated. However, it may be noted that the correlations observed with $d = 0$ are consistently lower than those predicted theoretically. The discrepancy may not be significant but, if it is real, it was possibly caused by defects in the optical system. In particular, the image of the arc showed striations due to imperfections in the glass bulb of the lamp; this implies that unwanted differential phase-shifts were being introduced which would tend to reduce the observed correlation.

This experiment shows beyond question that the photons in two coherent beams of light are correlated, and that this correlation is preserved in the process of photoelectric emission. Furthermore, the quantitative results are in fair agreement with those predicted by classical electromagnetic wave theory and the correspondence principle. It follows that the fundamental principle of the interferometer represented in Fig. 1*b* is sound, and it is proposed to examine in further detail its application to visual astronomy. The basic mathematical theory together with a description of the electronic apparatus used in the laboratory experiment will be given later. 中

We thank the Director of Jodrell Bank for making available the necessary facilities, the Superintendent of the Services Electronics Research Laboratory for the loan of equipment, and Mr. J. Rodda, of the Ediswan Co., for the use of two experimental phototubes. One of us wishes to thank the Admiralty for permission to submit this communication for publication. 中文

(177, 27-29; 1956)

R. Hanbury-Brown: University of Manchester, Jodrell Bank Experimental Station.

R. Q. Twiss: Services Electronics Research Laboratory, Baldock.

References:

1. Hanbury Brown, R., and Twiss, R. Q., *Phil. Mag.*, **45**, 663 (1954).
2. Jennison, R. C., and Das Gupta, M. K., *Phil. Mag.* (in the press).

两个相干光束中光子间的相关性

汉伯里-布朗，特威斯

在经典的干涉技术中，由两个相互作用光束之间的相位差可以探查出它们传播路径的不同。20世纪50年代早期，罗伯特·汉伯里-布朗和理查德·特威斯提出了一种新的干涉测量法，此方法仅仅利用光强（非相位）就可以估测遥远恒星的角大小。本文中他们报道了对这种效应所做的实验论证。结果阐释了光子的量子“聚束”效应——两束独立的相干光束中的光子有同时到达两个探测器的趋势。现在，汉伯里-布朗-特威斯效应一般是指使用两个探测器测量出的从一个粒子束发出的信号强度之间的任何相关性或者反相关性。强度干涉法已经成为核物理以及粒子物理中一项重要的技术。

英文

在一篇早期的论文中^[1]，我们描述了一台新型的干涉仪，它已被用于测量射电星的角直径^[2]。用这台仪器分别检测来自 A_1 和 A_2 两个天线（如图1a所示）的信号，并记录检测器低频输出之间的相关系数。因此我们没有测量到两个射电信号的相对相位，而仅测量到它们强度起伏的相关系数；这种原理与常见的迈克尔逊干涉仪的原理有根本上的差异，因为后者的信号是在检测前合成的，从而必然保留它们的相对相位。

英文

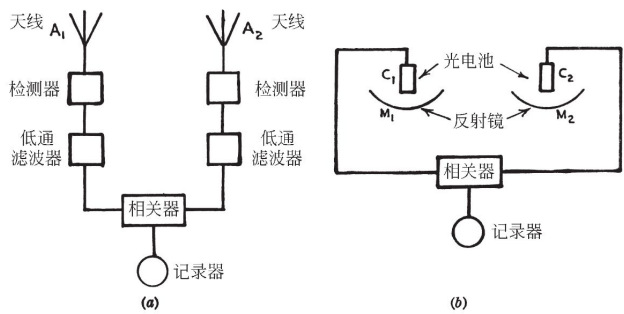


图1．新型射电干涉仪（a）及其在光学波段的类似设备（b）

英文

开发这套新系统是为了利用甚长基线，实验证明它在很大程度上不受电离层闪烁效应的影响^[2]。鉴于这套系统的优点，我们提出^[1]从原理上它可以用于测量目视恒星的角直径。因此我们可以用 M_1 和 M_2 两面反射镜来代替 A_1 和 A_2 两根天线（如图1b所示），用光电池 C_1 和 C_2 作为射频检测器，将测量到的由恒星照射导致的电池中电流起伏间的相关系数作为反射镜间距的函数。

英文

当然，当入射到两个反射镜上的光束有相干性时，光子到达两个光电阴极的时间应该是相关的，这对于这套系统的运行是很有必要的。然而，据我们所知，目前尚未用光直接观测到这个基本效应，况且此效应存在与否还存在疑问。此外，在光电发射过程中，无法确定是否完全保留着这种相关性。为此，我们开展了下列实验。

英文

图2展示了此套装置的概略图。一个截面为0.13毫米×0.15毫米的小矩形孔径形成光源，高压汞灯在此截面上聚焦成像。我们通过滤波系统将4,358埃的谱线分离出来，光束通过半透半反分束镜 M 被分成两束，分别照射在光电倍增管 C_1 和 C_2 的阴极上。这两个阴极与光源相距2.65米，它们的面积受到截面为9.0毫米×8.5毫米的相同矩形孔径 O_1 和 O_2 的限制。（可以证明这类仪器的两个阴极与光源之间的距离并不需要精确相等。在目前的实验中，它们的距离只是大致相等，精度约为1厘米。）为了使两束光束的相干度可以任意改变，光电倍增管 C_1 装在水平轨道上，这样光电倍增管 C_1 可以在垂直于入射光的方向上移动。因此从光源看来，两个阴极孔径能叠加或分离到最大可达约为其自身宽度3倍的任何量值。在3兆周/秒~27兆周/秒波段内来自光电倍增管的输出电流的起伏被放大，并在线性混频器中倍增。在积分电机的旋转计数器上记录乘积的平均值，并对起伏相关系数进行度量。为了得到有意义的结果，必须要对量级1小时的周期进行积分，所以我们非常精心地设计了电子装置，从而消除由漂移、干涉和放大器噪声所造成的影响。

英文

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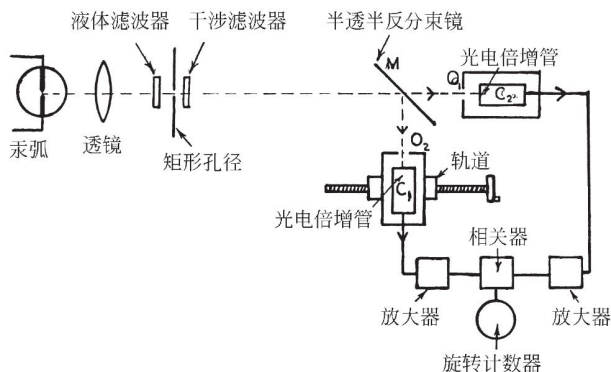


图2 . 装置的简化图 英文

假设发射一个光电子的概率与入射光的振幅的平方成正比，我们可以用经典电磁波理论计算来自两个阴极的电流起伏之间的相关系数。根据这个假设我们可以证明，两个阴极叠加，相关系数 $S(0)$ 由下式表示：

$$S(0) = A \cdot T \cdot b_v f\left(\frac{a_1 \theta_1 \pi}{\lambda_0}\right) \cdot f\left(\frac{a_2 \theta_2 \pi}{\lambda_0}\right) \int \alpha^2(v) \cdot n_0^2(v) \cdot dv \quad (1)$$

同样地，相应的方均根涨落 N 由下式给出：

$$N = A \cdot T \cdot \frac{2m}{m-1} \cdot b_v (b_v T)^{-\frac{1}{2}} \int \alpha(v) \cdot n_0(v) \cdot dv \quad (2)$$

式中 A 是与放大器增益等有关的比例常数； T 是观测时间； $\alpha(v)$ 是光电阴极在频率 v 处的量子效率； $n_0(v)$ 是每秒钟每周带宽入射到光电阴极上的量子数； b_v 是放大器的带宽； $m/(m-1)$ 是次级倍增引入的常见过量噪声； a_1 和 a_2 是光电阴极孔径的水平尺寸和垂直尺寸； θ_1 和 θ_2 是从光电阴极来看光源的角尺寸； λ_0 是光的平均波长。在假定光电管完全相同

的情况下，对整个光谱积分。因子 $f\left(\frac{a\theta\pi}{\lambda_0}\right)$ 由无量纲参数 η 决定， η 的定义为：

$$\eta = a\theta/\lambda_0 \quad (3)$$

这是光在光电阴极范围内相干度的度量。当 $\eta \ll 1$ 时，对于点光源， $f(\eta)$ 可有效地认定为单位1；然而，在实验室中做实验时，可方便地证明：设置 η_1 和 η_2 为单位1的数量级，以增加阴极上的入射光，从而提

高信噪比。此时对应的 $f(\eta_1)$ 和 $f(\eta_2)$ 的值分别是0.62和0.69。

英文

当从源处看阴极的中心水平方向上位移距离为 d 时，相关系数的理论值会降低，它的多少与无量纲参量 η_1 和 d/a_1 有关。在简单情况下 $\eta_1 \ll 1$ ，将其用于可视恒星的实验上，可以证明相关系数 $S(d)$ 作为 d 的函数与等效线源上强度分布的傅里叶变换的平方成正比。然而，当 $\eta \geq 1$ 时，正如在目前的实验中一样，相关系数是由阴极的表观叠加有效决定的，而并不严格地依赖于源处的实际宽度。因此，在目前的实验中我们并不试图测量源的视角大小。

英文

最初的实验观测是在光电阴极有效地叠加（ $d=0$ ）以及改变照明强度下进行的。在我们所预期的所有情况下，当光电阴极相距很远时，观测到相关系数为正的情况完全消失。在第一批实验中，光电阴极的量子效率太低，以致没有得到令人满意的信噪比。然而，当我们采用具有较高量子效率的改进型光电倍增管时，就能进行这个理论的定量检验。

英文

我们所做的观测4次为一组、每次持续时间为90分钟，是在阴极叠加（ $d=0$ ）时进行的。计数器以5分钟为时间间隔进行记录。根据这些读数，我们对 N_e 做出估测，其中 N_e 为计数器最终读数 $S(0)$ 的均方根偏差，将 $S_e(0)/N_e$ 的观测值列入表1的第1列内。为了消除（1）式和（2）式中的因子 A ，结果以比值的形式给出，此比值受装置增益变化的影响。对每次测量的因子如下式所示：

$$\frac{m-1}{m} \int \alpha^2(v) n_0^2(v) dv / \int \alpha(v) n_0(v) dv$$

这是由入射光的光谱、直流电流、增益和光电倍增管的输出噪声所决定的；表1的第2列内示出了 $S_e(0)/N_e$ 相应的理论值。在典型情况下，光电倍增管的增益是 3×10^5 ，输出电流是140微安，量子效率 $\alpha(v_0)$ 的数量级为15%， $n_0(v_0)$ 的数量级为 3×10^{-3} 。在每次测量之后，在光电阴极中心做一次对比测量，从源处看两阴极之间的距离为自身宽度的两倍（ $d=2a$ ），在光电阴极中心时理论修正实际上为零。表1的第3列内列出的是 $S_e(d)$ 与 N_e 的比值，其中 $S_e(d)$ 是90分钟后的计数器读数， N_e 是

表1. 相关系数的理论值和实验值之间的比较

阴极叠加 ($d = 0$)		阴极分离 ($d = 2a = 1.8$ 厘米)	
相关系数与均方根偏差 的实验比 $S_e(0)/N_e$	相关系数与均方根偏差 的理论比 $S(0)/N$	相关系数与均方根偏差 的实验比 $S_e(d)/N_e$	相关系数与均方根偏差 的理论比 $S(d)/N$
1 +7.4	+8.4	-0.4	~0
2 +6.6	+8.0	+0.5	~0
3 +7.6	+8.4	+1.7	~0
4 +4.2	+5.2	-0.3	~0

英文

表1中所示的结果证实了在阴极叠加时可观测到相关性，但当阴极相距甚远时未观测到相关性。然而可以注意到的是，距离 $d = 0$ 时实验所观测到的相关系数比理论上预料的数值一致偏低。这个差异可能并不重要，但如果事实如此，那么它可能是由光学系统中的缺陷引起的。尤其是灯的玻璃泡中的不完善性引起弧光的像呈现辉纹，这意味着引入了多余的微分相移，它们往往会降低观测到的相关系数。

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这项实验表明，两束相干光的两个光子之间的相关性是毫无疑问的，这种相关性存在于光电发射的过程中。此外，定量结果与经典电磁波理论及相应原理的预料吻合得相当好。图1b所示干涉仪的基本原理是正确的，建议在目视天文学的应用中进行进一步详细的检验。基本数学理论与用于实验室的电子学装置的描述将在以后一起给出。

英文

我们感谢焦德雷尔班克天文台台长允许我们使用所需的实验设备，同时对电子服务研究实验室的负责人所提供的实验设备表示感谢，还要对爱迪斯旺公司的罗达先生所提供的两个光电管表示感谢。我们当中的一位作者对英国海军部同意将此文予以发表表示感谢。

英文

（ 沈乃澂 翻译；熊秉衡 审稿）

The Neutrino

F. Reines and C. L. Cowan

The existence of the subatomic particle called the neutrino had been inferred in the early 1930s chiefly as a result of work by Enrico Fermi in Rome and Wolfgang Pauli in Zurich from the phenomenon of radioactive beta-decay: it was supposed to be a particle with insignificant mass and no electric charge. Frederick Reines and Clyde L. Cowan at the Los Alamos Scientific Laboratory, acknowledging that nuclear reactors should be powerful sources of neutrinos, here described an experiment to demonstrate the existence of neutrinos by their interaction with protons (provided by a large tank of water) and their individual conversion into photons which were to be measured by an array of photoscintillators. The use of photoscintillators for detecting neutrinos produced in analogous nuclear reactions has become standard practice. In the 1980s, however, it became clear that there are three different kinds of neutrinos and that even those studied by Reines and Cowan may have a small mass. [中文](#)

EACH new discovery of natural science broadens our knowledge and deepens our understanding of the physical universe; but at times these advances raise new and even more fundamental questions than those which they answer. Such was the case with the discovery and investigation of the radioactive process termed “beta decay”. In this

process an atomic nucleus spontaneously emits either a negative or positive electron, and in so doing it becomes a different element with the same mass number but with a nuclear charge different from that of the parent element by one electronic charge. As might be expected, intensive investigation of this interesting alchemy of Nature has shed much light on problems concerning the atomic nucleus. A new question arose at the beginning, however, when it was found that accompanying beta decay there was an unaccountable loss of energy from the decaying nucleus¹, and that one could do nothing to the apparatus in which the decay occurred to trap this lost energy². One possible explanation was that the conservation laws (upon which the entire structure of modern science is built) were not valid when applied to regions of subatomic dimensions. Another novel explanation, but one which would maintain the integrity of the conservation laws, was a proposal by Wolfgang Pauli in 1933 which hypothesized a new and fundamental particle³ to account for the loss of energy from the nucleus. This particle would be emitted by the nucleus simultaneously with the electron, would carry with it no electric charge, but would carry the missing energy and momentum—escaping from the laboratory equipment without detection. [中文](#)

The concept of this ghostly particle was used by Enrico Fermi (who named it the “neutrino”) to build his quantitative theory of nuclear beta decay⁴. As is well known, the theory, with but little modification, has enjoyed increasing success in application to nuclear problems and has itself constituted one of the most convincing arguments in favour of the acceptance of Pauli’s proposal. Many additional experimental tests have been devised, however, which have served to strengthen the neutrino hypothesis; and also to provide information as to its properties. The very characteristic of the particle which makes the proposal plausible—its ability to carry off energy and momentum without detection—has limited these tests to the measurement of the observable details of the decay process itself: the energy spectra,

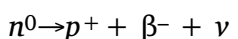
momentum vectors and energy states associated with the emitted electron and with the recoiling daughter nucleus⁵. So, for example, an upper limit has been set on the rest mass of the neutrino equal to 1/500 of the rest mass of the electron by careful measurement of the beta-energy spectrum from tritium decay near its end point⁶, and it is commonly assumed that the neutrino rest mass is identically zero.

[中文](#)

While there is no theoretical reason for the expectation of a finite neutrino rest mass, there is some expectation for a small but finite neutrino magnetic moment of perhaps as much as 10^{-10} Bohr magneton based on a consideration of possible virtual states in which the neutrino may exist effectively dissociated into other particles⁷. An upper limit of 2×10^{-9} electron Bohr magneton has been set on the magnetic moment by calculations concerning the maximum assignable heat transfer to the Earth by neutrinos from the Sun⁸. We have recently obtained an improved upper limit of 10^{-9} electron Bohr magneton using a large scintillation detector near a fission reactor at the Savannah River Plant of the United States Atomic Energy Commission. The counting rate of single pulses in an energy range of 0.1–0.3 MeV. in 370 gallons of liquid scintillator was observed, and all changes due to reactor power changes were assigned to possible electron recoils in the liquid through magnetic moment interaction with neutrinos. It is hoped that this limit may be further improved by lowering the gamma-ray and neutron background at the detector.

[中文](#)

The Pauli-Fermi theory not only requires the neutrino to carry energy and linear momentum from beta-decaying nuclei but also angular momentum, or “spin”. The simplest of beta-decay processes, the decay of the free neutron⁹, illustrates this:



(1)

As the neutron, proton and beta particle all carry half-integral spin, it is necessary to assign a spin quantum number of 1/2 to the neutrino to balance the angular momenta of equation (1), where any two of the three product particles must be oriented with spin vectors antiparallel. As all four of the particles in equation (1) are, therefore, fermions and should obey the Dirac relativistic Wave equations for spin 1/2 particles, there are presumably antiparticles corresponding to each, of which as yet only the anti-electron (or positron) and the antiproton have been identified. The antiparticle corresponding to the neutrino in equation (1) may be obtained by rearrangement of the terms in the following manner:

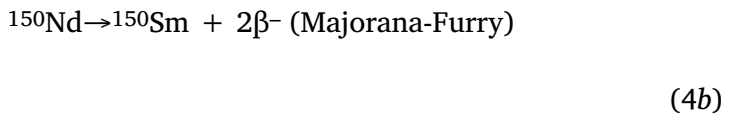
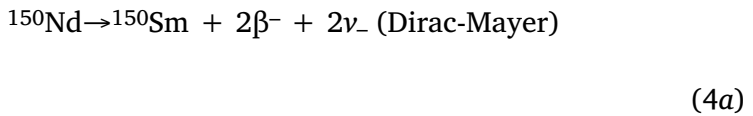
$$p^{+} \rightarrow n^{0} + \beta^{+} + \nu_{+} \quad (2)$$

This process is observed in positron decay of proton-rich radioactive nuclides where the proton and daughter neutron are both constituent nucleons. Further rearrangement results in the reaction:

$$\beta^{-} + p^{+} \rightarrow n^{0} + \nu_{+} \quad (3)$$

This is descriptive of the capture of an electron from one of the inner atomic shells by a nuclear proton and is equivalent to equation (2). The question of the identity of the neutrino, ν_{+} , appearing in equations (2) and (3) with the neutrino, ν_{-} , appearing in equation (1) thus arises. With no finite mass or magnetic moment yet measured for either of the neutrinos, one is under no compulsion to assume that they are not in fact identical. The rule of algebraic conservation of fermions, which states that fermions are produced or disappear in particle-antiparticle pairs, requires the ν_{-} of equation (1) to be named

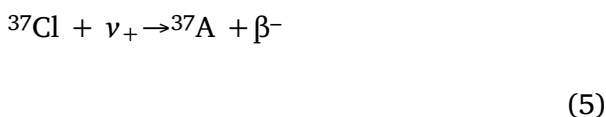
“antineutrino”, since it is emitted with a negative electron. The identity or non-identity of the neutrino, ν_+ , and the antineutrino, ν_- , although of no observable significance in single beta decay, should be amenable to test by measurement of the decay constant for double beta decay of certain shielded isotopes. This process was studied theoretically by M. Goeppert-Mayer¹⁰ for the case in which neutrinos are not identical with antineutrinos and by Furry¹¹ for the case in which the two neutrinos are identical, as proposed by Majorana¹². Double beta decay is typified by the possible decay of neodymium-150:



If the neutrino and antineutrino are identical, then the virtual emission of one neutrino and its immediate re-absorption by the nucleus are equivalent to the real emission of two neutrinos, and equation (4b) is applicable. This cancellation is not possible if the neutrino and antineutrino differ. The half-lives for processes such as equation (4) have been shown by Primakoff¹³ and by Konopinski¹⁴ to be quite different in the two cases, of the order 10^{19} years for equation (4a) and 10^{15} years for equation (4b), where 5.4 MeV. is available for the decay. Furthermore, a line spectrum for the total energy of the two beta particles is to be expected for the Majorana-Furry case (equation 4b). [中文](#)

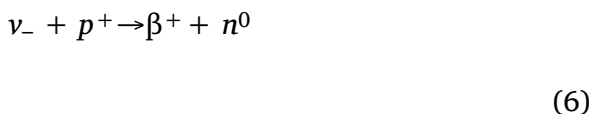
That a decay period consistent with equation (4b) does not exist has been shown for a number of shielded isotopes¹⁵, first by Kalkstein and Libby, then by Fireman and Schwartz for tin-124; by Awschalom for calcium-48; and our associates and us for neodymium-150. In the

neodymium-150 experiment, a lower limit of 4×10^{18} years (corresponding to one standard deviation in the background) was set on the mean life against Majorana-Furry decay. This limit is to be compared with a reasonable value on this hypothesis of 1.3×10^{15} years and one calculated for identical neutrinos (using most severe assumptions) to be 6×10^{17} years. The conclusion remains that the neutrino and antineutrino are distinct particles with an as yet undetected “difference”. This conclusion is further supported by the negative results of an experiment recently reported by R. Davis¹⁶ employing the reaction:



The chlorine target was supplied by 1,000 gallons of carbon tetrachloride placed near a large reactor, and the liquid was tested for the presence of argon-37. Fission fragments, being rich in neutrons, should emit only the antineutrino, ν_- . 中文

While careful reasoning from experimental evidence gathered about all terms in the beta-decay process—except the neutrino—may support the inference that a neutrino exists, its reality can only be demonstrated conclusively by a direct observation of the neutrino itself. If the neutrino is a real particle carrying the missing energy and momentum from the site of a beta decay, then the discovery of these missing items at some other place would demonstrate its reality. Thus, if negative beta decays as in equation (1) could be associated at another location with the inverse reaction:



which is observed to occur at the predicted rate, the case would be

closed. An expression for this reaction cross-section has been obtained by application of the principle of detailed balancing to equation (1), knowing the decay constant and electron energy spectrum for the beta decay of free neutrons:

$$\sigma = \left(\frac{G^2}{2r}\right) \left(\frac{\hbar}{mc}\right)^2 \left(\frac{p}{mc}\right)^2 \left(\frac{1}{v/c}\right)^2 (\text{cm.}^2) \quad (7)$$

where σ is the cross-section in cm.^2 ; G^2 ($=44 \times 10^{-24}$) is the dimensionless lumped beta-coupling constant based on neutron decay⁹; and p , m and v are the momentum, mass and speed of the emitted positron, respectively, c is the speed of light, and $2\pi\hbar$ is Planck's constant, all in c.g.s. units. For neutrinos of 3-MeV. energy incident on free protons, this cross-section is 10^{-43} cm.^2 . Explicit solution of equation (6) for the cross-section as a function of the neutrino energy yields:

$$\sigma = 1.0 \times 10^{-44} \times (E - a) \sqrt{(E - a)^2 - 1} (\text{cm.}^2) \quad (8)$$

where $a+1$ ($=3.53$) is the threshold for the reaction and E is the neutrino energy, both in units of $m_e c^2$. The threshold for a proton bound in a nucleus is higher by an amount equal to the energy difference between the target and daughter nuclei. It is interesting to note that the penetrability of matter is given by equation (8) to be infinite for neutrinos with low energies ($E < a+1$) and is very large for neutrinos of only a few MeV., the mean free path for absorption being measured in the latter case in terms comparable to the radius of the universe. [中文](#)

Equation (6) may be employed in an experiment in which a large number of hydrogen atoms are provided as targets for an intense neutrino flux and are watched by a detector capable of recording the simultaneous production of a positron and a neutron. Such a direct experiment is made possible by the availability of high beta-decay rates of fission fragments in multi-megawatt reactors and advances in

detection techniques through the use of liquid scintillators. An estimate of the neutrino flux available from large reactors shows that a few protons should undergo reaction (6) per hour in 50 litres of water placed near the reactor. The problem, then, is to observe these events with reasonable efficiency against the background of reactor neutrons and gamma-rays, natural radioactivity and cosmic rays. In an experiment conducted at the Hanford Plant of the Atomic Energy Commission by us¹⁷ in 1953, an attempt was made in this direction. The target protons were supplied by 300 litres of liquid scintillator (toluene plus trace amounts of terphenyl, and alpha-naphthaphenyloxayole in which cadmium propionate was dissolved). A delayed coincidence-rate of pairs of pulses, the first of each pair being assignable to the positron and the second to a neutron capture in cadmium, of 0.4 ± 0.2 counts per minute was observed, in agreement with the predicted rate, and with a large reduction in the backgrounds mentioned above. The signal-to-total-background ratio, however, was still very low (1/20), rendering further testing of the signal impractical and leaving the results tentative. On the basis of the Hanford experience it was felt that the detection problem was soluble in a definitive manner, and a second experiment was designed¹⁸ with the view of further reduction of backgrounds and providing means for checking each term of equation (6) independently. 中文

Fig. 1 is a schematic diagram of the detection scheme employed in this experiment. The sequence of events pictured is as follows: a neutrino from the decay of a fission fragment in a reactor causes a target proton to be changed into a neutron with the simultaneous emission of a positron. The positron is captured by an electron in the target water, emitting two 0.51-MeV. annihilation gamma-rays, which are detected simultaneously by counters I and II. The neutron moderates and diffuses for several microseconds and is finally captured by the cadmium giving a few gamma rays (totalling 9 MeV.), which are again detected by I and II. Thus we have a prompt coincidence followed in

several microseconds by a second prompt coincidence, providing a very distinctive sequence of events. 中文

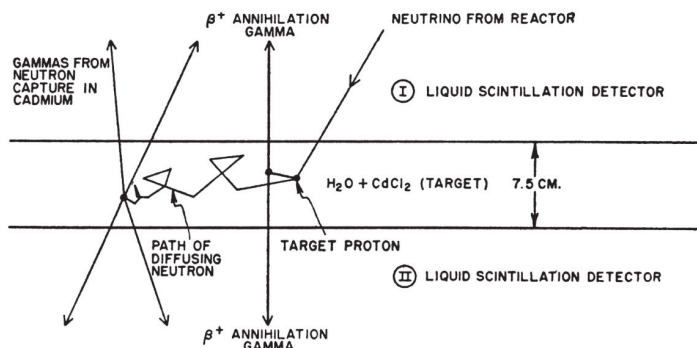


Fig. 1. Schematic diagram of neutrino detector 中文

The over-all size of the equipment was set by the number of events expected per hour per litre of water, and the detection efficiency one could hope to achieve. A primary factor in the design geometry and detection efficiency was the absorption of the positron annihilation radiation by the target water itself. Experimentation and calculations showed that an optimum water thickness was 7.5 cm. Since the over-all efficiency dictated a target volume of about 200 litres to yield several counts per hour, two target tanks were used, each measuring 1.9 m. $\times$ 1.3 m. $\times$ 0.07 m. The depth of the liquid scintillation detector (61 cm.) was such as to absorb the cadmium-capture gamma-rays with good efficiency and transmit the resultant light to the ends of the detector with minimal loss. The scintillating liquid (triethylbenzene, terphenyl and POPOP wave-length shifter) were viewed from the ends of each detector tank by 110 5-in. Dumont photomultiplier tubes, a number determined primarily by the amount of light emitted in a scintillation. The complete detector consisted of a "club sandwich" arrangement employing two target tanks between three detector tanks, comprising two essentially independent triads which used the centre detector tank in common. The entire detector was encased in a lead-paraffin shield and located deep underground near one of the Savannah River Plant production reactors of the

United States Atomic Energy Commission. Signals from the detectors were transmitted via coaxial cables to an electronics trailer located outside the reactor building. The pulses were analysed by pulse-height and time-coincidence circuits and, when acceptable, were recorded photographically as traces on triple-beam oscilloscopes. Fig. 2 is a record of an event in the bottom triad. The entire system was calibrated using a plutonium-beryllium neutron source and a dissolved copper-64 positron source in the target tanks; and standardized pulsers were used to check for stability of the electronics external to the detector itself. The response of the detector to cosmic ray μ -mesons was also employed as a check on its performance. After running for 1,371 hr., including both reactor-up and reactor-down time, it was observed¹⁹ that:

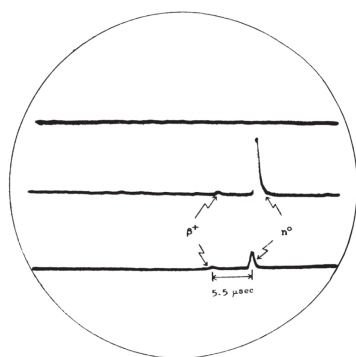


Fig. 2. A characteristic record. Each of the three oscilloscope traces shown corresponds to a detector tank. The event recorded occurred in the bottom triad. First seen in coincidence are the “positron” annihilation gamma-ray pulses in each tank followed in 5.5 μ sec. by the larger “neutron” pulses. The amplification was chosen in this case to enable measurement of the neutron pulses. A second oscilloscope with higher amplification was operated in parallel to enable measurement of the positron pulses

中文

(1) A signal dependent upon reactor-power, 2.88 ± 0.22 counts/hr. in agreement with the predicted²⁰ cross-section (6×10^{-44} cm.²), was measured with a signal-to-reactor associated accidental background in excess of 20/1. The signal-to-reactor independent background ratio was 3/1.

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(2) Dilution of the light water solution in the target tank with heavy

water to yield a proton density of one-half normal caused the reactor signal to drop to one-half its former rate. The efficiency of neutron detection measured with the plutonium-beryllium source was unchanged. [中文](#)

(3) The first pulse of the pair was shown to be positron annihilation radiation by subjecting it to a number of tests: its spectrum agreed with the spectrum of positron annihilation radiation from copper-64 dissolved in the water, and it was absorbed in the expected manner by thin lead sheets inserted between the target tank and one detector.

[中文](#)

(4) The second pulse of the pair was identified as due to the capture in cadmium of a neutron born simultaneously with the positron by virtue of its capture-time distribution as compared both with calculations and observations with a neutron source. The second pulse spectrum was consistent with that of cadmium-capture gamma-rays, and removal of the cadmium resulted in disappearance of the reactor signal. [中文](#)

(5) Reactor-associated radiations such as neutrons and gamma-rays were ruled out as the source of the signal by two kinds of experiment. In the first, a strong americium-beryllium neutron source was placed outside the detector shield and was not only found very inefficient in producing acceptable delayed coincidences but was also found to produce a first-pulse spectrum which was unlike the required signal in that it was monotonically decreasing with increasing energy. In the second experiment an additional shield, which provided an attenuation factor of at least 10 for reactor neutrons and gamma-rays, was observed to cause no change in the reactor signal outside the statistical fluctuations quoted in (1). [中文](#)

Completion of the term-by-term checks of equation (6) thus demonstrated that the free neutrino is observable in the near vicinity

of a high-power fission reactor.

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The availability of neutrinos from reactors in sufficiently intense fluxes has opened a number of interesting possibilities. One arises from the use of heavy water to dilute the proton target as described above. This test was valid because the threshold for the neutrino interaction with the deuteron is higher by 2.2 MeV., the binding energy of the deuteron, than the threshold energy for equation (6), and the cross-section is for this reason an order of magnitude smaller; other considerations reduce it still further. The neutrino-deuteron interaction is itself, however, of interest, as two alternatives arise:

$$\nu_- + D \rightarrow \beta^+ + n + n \quad (8a)$$

$$\nu_- + D \rightarrow \beta^+ + n_2 \quad (8b)$$

where n_2 is the bound state of the dineutron²¹, as yet unobserved. If reaction (8a) were observed to occur, then a careful measurement of its rate relative to the rate of reaction (6) and a knowledge of the fission neutrino spectrum should enable a direct determination of the ratio of the Fermi and Gamow-Teller coupling constants in beta decay. This follows from the fact that the coupling constant in equation (6) includes a mixture of both types, whereas in (8a) it is composed of the Gamow-Teller constant alone. If, on the other hand, equation (8b) were observed, not only would these considerations hold, but also the existence of a bound state of the dineutron, which would necessarily be a singlet state (antiparallel spins) because of the Pauli exclusion principle, would bear directly on the question of the dependence of nuclear forces on charge. This follows because the singlet state of the (n, p) system is known to be unbound. As the two neutrons in equation (8a) can possess only a few kilovolts of energy when

produced by fission-fragment neutrinos, and as they leave the event in antiparallel spin states, the conditions seem favourable for the formation of dineutrons, even if the binding energy were only tens of kilovolts. [中文](#)

Since the proposal of the neutrino hypothesis by Pauli and its success in Fermi's theory of nuclear beta decay, the particle has been called upon to play similar parts in the observed decay of a number of different mesons²². The question arises as to the identity of these neutrino-like particles with the neutrino of nucleon decay. It is to be noted that in nuclear beta decay the initial and final nuclei both quite obviously interact strongly with nuclei. This is not the case in (π, μ) decay, where the emission of a "neutrino" converts the interaction of the heavy particles with nuclei from strong to weak. Furthermore, despite the apparent equality of the nuclear beta-decay matrix elements with those associated with (μ, β) decay, both the initial and final products of the latter interact weakly with nuclei. [中文](#)

The neutrino is the smallest bit of material reality ever conceived of by man; the largest is the universe. To attempt to understand something of one in terms of the other is to attempt to span the dimension in which lie all manifestations of natural law. Yet even now, despite our shadowy knowledge of these limits, problems arise to try the imagination in such an attempt. If nuclear reactions played a part in a cataclysmic birth of the universe as we assume, what fraction of the primordial energy was quickly drained into the irreversible neutrino field? Are these neutrinos—untouched by anything from almost the beginning of time—trapped by the common gravitational field of the universe, and if so, what is their present density, their energy spectrum and angular distribution? Do neutrinos and antineutrinos exist in equal numbers? If the neutrino has zero rest mass, is it to be considered with "matter" particles in discussing its gravitational potential, or with electromagnetic radiation? The

problem of detecting these cosmic end-products of all nuclear energy generation processes and the measurement of their characteristics presents a great challenge to the physics of today. 中文

The known properties of the neutrino are summarized below.

Properties of the Neutrino

Spin	$1/2\hbar$.
Mass	$<1/500$ electron mass, if any.
Charge	0.
Magnetic moment	$<10^{-9}$ Bohr magneton
Cross-section for reaction	$\nu + p^+ \rightarrow \beta^+ + n^0$ at 3 MeV. $\approx 10^{-43}$ cm. ² . Neutrino ν_e not identical with antineutrino $\bar{\nu}$.

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Our work and that of our associates reported in this paper were supported by the United States Atomic Energy Commission. 中文

(178, 446-449; 1956)

Frederick Reines and Clyde L. Cowan, jun.: University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico.

References:

1. Chadwick discovered that the beta spectrum was continuous. L. Meitner suggested in 1922 that a quantized nucleus should not be expected to emit a continuous spectrum, and Ellis found non-conservation of energy from experiments on the emitted electron. Chadwick, J., *Verh. Deutsch. Phys. Ges.*, **16**, 383 (1914). Ellis, C. D., *Internat. Conf. on Phys.*, **16**, 209 (1934).
2. Ellis and Wooster, *Proc. Roy. Soc., A*, **117**, 109 (1927). Chadwick, J., and Lea, D. E., *Proc. Camb. Phil. Soc.*, **30**, 59 (1934); Nahmias, M. E., *Proc. Camb. Phil. Soc.*, **31**, 99 (1935). Wu, C. S., *Phys. Rev.*, **59**, 481 (1941).
3. Pauli, W., in “Rapports du Septième Conseil de Physique Solvay”, Brussels, 1933 (Gauthier-Villars, Paris, 1934).
4. Fermi, E., *Z. Phys.*, **88**, 161 (1934).
5. We do not attempt here to describe the many beautiful and difficult, recoil experiments in which recoils of neutrino-emitting nuclei (~8-200 eV.) have been measured. A summary can be found in an article by O. Kofoed-Hansen in Siegbahn’s “Beta and Gamma-Ray Spectroscopy” (Interscience Publishers, Inc., New York, 1955).
6. Langer, L. M., and Moffat, R. J. D., *Phys. Rev.*, **88**, 689 (1952). Hamilton, Alford and Gross, *Phys. Rev.*, **92**, 1521 (1953). This question is treated in detail in an article by C. S.

- Wu in Siegbahn (*op. cit.*). We quote Dr. Wu's most conservatively estimated limit.
7. Houtermans, F. G., and Thirring, W., *Helv. Phys. Acta*, **27**, 81 (1954). H. A. Bethe has given the relationship between the recoil electron spectrum and the energy and magnetic moment of a neutrino in *Proc. Camb. Phil. Soc.*, **31**, 108 (1935).
 8. Crane, H. R., *Revs. Mod. Phys.*, **20**, 278 (1948). This article also summarizes neutrino detection attempts to 1948. The status of the neutrino in 1936 is given by H. A. Bethe and R. F. Bacher. *Revs. Mod. Phys.*, **8**, 82 (1936).
 9. Snell, A. H., and Miller, L. C., *Phys. Rev.*, **74**, 1714 A (1948). Snell, A. H., Pleasanton, F., and McCord, R. V., *Phys. Rev.*, **78**, 310 (1950). Robson, J. M., *Phys. Rev.*, **78**, 311 (1950); **83**, 349 (1951).
 10. Goeppert-Mayer, M., *Phys. Rev.*, **48**, 512 (1935).
 11. Furry, W. H., *Phys. Rev.*, **56**, 1184 (1939).
 12. Majorana, E., *Nuovo Cimento*, **14**, 171 (1937).
 13. Primakoff, H., *Phys. Rev.*, **85**, 888 (1952).
 14. Konopinski, E. J., Los Alamos Report LAMS 1949 (1955).
 15. Kalkstein, M. I., and Libby, W. F., *Phys. Rev.*, **85**, 368 (1952). Fireman, E. L., and Schwartz, D., *Phys. Rev.*, **86**, 451 (1952). Awschalom, M., *Phys. Rev.*, **101**, 1041 (1956). Cowan, jun., C. L., Harrison, F. B., Langer, L. M., and Reines, F., *Nuovo Cimento*, **3**, 649 (1956).
 16. Davis, jun., R., Contributed Paper, American Physical Society, Washington, D. C., Meeting, 1956. This experiment was originally suggested by Pontecorvo and considered by Alvarez in a report UCRL-328 (1949).
 17. Reines, F., and Cowan, jun., C. L., *Phys. Rev.*, **90**, 492 (1953); **92**, 830 (1953).
 18. Cowan, jun., C. L., and Reines, F., Invited Paper, American Physical Society, New York Meeting, January 1954.
 19. Cowan, jun., C. L., and Reines, F., Postdeadline Paper, American Physical Society, New Haven Meeting, June 1956. Cowan, Reines, Harrison, Kruse and McGuire, *Science*, **124**, 103 (1956).
 20. The neutrino spectrum was deduced from the spectrum of beta-radiation from fission fragments as measured by C. O. Muehlhause at the Brookhaven National Laboratory. Dr. Muehlhause kindly communicated his results to us in advance of publication.
 21. The evidence for and against the existence of a "bineutron", also called "dineutron", is discussed by B. T. Feld in his article on the neutron in the volume edited by E. Segrè entitled "Experimental Nuclear Physics", 2 (John Wiley and Sons, Inc., New York, 1953).
 22. Oneda, S., and Wakasa, A., discuss the question of classes of interactions between the elementary particles in *Nuclear Phys.*, **1**, 445 (1956).

中微子

莱因斯，考恩

20世纪30年代初期，罗马的恩里科·费米和苏黎世的沃尔夫冈·泡利根据放射性 β 衰变现象得到的研究结果，推测出被称为中微子的亚原子粒子的存在，他们认为该粒子质量极小且不带电荷。洛斯阿拉莫斯科学实验室的弗雷德里克·莱因斯和克莱德·考恩认为，核反应堆是强大的中微子源，本文中他们描述了一个证明中微子存在的实验，实验中质子（由一大箱水提供）与中微子相互作用，使中微子转换为光子，并用光闪烁体阵列对光子进行测量。如今用光闪烁体检测这类核反应中产生的中微子已成为标准方法。然而，直到20世纪80年代人们才逐渐清楚存在三种不同类型的中微子以及莱因斯和考恩研究的那些中微子也可能具有微小的质量。 [英文](#)

自然科学的每项新发现都扩展了我们的知识，加深了我们对物质世界的了解；但是与它们所解决的问题相比，这些进展有时会引出一些新的甚至更基本的问题。放射性“ β 衰变”过程的发现和研究就是这样一个例子。在这个过程中，原子核自发地发射一个负电子或正电子，这样它就变成了一个与母元素质量数相同但相差一个电子电荷的不同元素。正如所预料的那样，对自然界这一有趣的神奇过程的深入研究阐明了关于原子核的一些问题。然而随即出现的一个新问题是：人们发现伴随着 β 衰变，衰变核^[1]中有无法解释的能量损失；并且人们无法通过改善发生衰变的装置来捕获这些损失的能量^[2]。一种可能的解释是，守恒定律（现代科学的整个结构建立在这个定律之上）应用到亚原子尺度时不再成立。沃尔夫冈·泡利于1933年提出另一种新奇的但能继续遵守守恒定律的解释，他假设存在一类新的基本粒子^[3]对应于损失的核能量。核在发射电子的同时发射出这类粒子，该粒子不带电荷，但是带有丢失的那部分能量和动量，即实验装置未检测到的那部分能量和动量。 [英文](#)

恩里科·费米在构建他的核 β 衰变定量理论^[4]时，采用了这个如幽灵般的粒子的概念（他称之为“中微子”）。众所周知，这个理论作了微小修正后应用到核问题中已经取得了越来越多的成功，并成为支持泡利观点的最令人信服的论据之一。此外，还设计了许多别的实验测试，这些测试巩固了中微子假设，并提供了中微子性质的信息。这种粒子具有带走能量和动量而不被检测到的本领，这表明之前提出的解释可能是正确的。也正是这一特性限制了这些测试只能测量衰变过程本身可观测的细节：与发射的电子和反冲子核^[5]相关的能谱、动量矢量和能态。例如，通过仔细测量接近端点的氘衰变的 β 能谱^[6]，得到中微子静止质量的上限为电子的静止质量的1/500，通常可以假定中微子的静止质量恒等于零。

英文

然而预测中微子确定的静止质量并无理论上的根据，但考虑到中微子可能存在的虚态（中微子在这种虚态中可以分裂为其他粒子^[7]），可以预测中微子具有很小且确定的磁矩，大小可能为 10^{-10} 玻尔磁子。通过计算中微子从太阳^[8]到地球所传送的最大可转让热量，得到磁矩的上限可取为 2×10^{-9} 电子玻尔磁子。最近我们在美国原子能委员会萨凡纳河工厂的裂变反应堆附近使用大的闪烁探测器，得到改进上限值为 10^{-9} 电子玻尔磁子。在370加仑的液体闪烁器内，观测到了0.1兆电子伏~0.3兆电子伏能量区间内单脉冲的计数率，通过与中微子的磁矩相互作用，由反应堆功率变化引起的所有变化都被归因于液体中可能的电子反冲。我们希望通过降低探测器中 γ 射线和中子的背景，可以进一步改进这个上限。

英文

泡利-费米理论不仅要求中微子从 β 衰变核带走能量和线性动量，而且还要求带走角动量，即“自旋”。最简单的 β 衰变过程就是自由中子的衰变^[9]，可用下式说明：

$$n^0 \rightarrow p^+ + \beta^- + \nu_- \quad (1)$$

因中子、质子和 β 粒子都带有半整数的自旋，为了式（1）中的角动量平衡（式中三个产物粒子中的任何两个必须自旋反平行），必须赋予中微子一个量子数为1/2的自旋。因为式（1）中四个粒子全都是费米子，所

以应遵从自旋为1/2的粒子的狄拉克相对论波动方程。每个粒子都可能存在相应的反粒子，但只有反电子（或称为正电子）和反质子已被确认。式（1）的中微子相应的反粒子可以通过把这几项重排而获得：

$$p^+ \rightarrow n^0 + \beta^+ + \nu_+ \quad (2)$$

这个过程是在丰质子放射性核素的正电子衰变中观测到的，其中质子和中子都是核子的组成成分。进一步的重排引起了如下反应：

$$\beta^- + p^+ \rightarrow n^0 + \nu_+ \quad (3)$$

与式（2）类似，这是一个核内质子从原子内壳层捕获电子的描述。这导致了一个问题，即式（2）和式（3）中的中微子 ν_+ 与式（1）中的中微子 ν_- 是否相同。目前二者的质量和磁矩都还没有确定的测量值，我们更倾向于认为它们实际上是相同的。费米子代数上的守恒法则表示，费米子是通过粒子-反粒子对成对产生或消失的，由于式（1）的 ν_- 是伴随一个负电子发射的，因此应被称为“反中微子”。尽管中微子 ν_+ 和反中微子 ν_- 是否相同这个问题在单一的 β 衰变中并无重要观测结果，但却易于通过测量某些屏蔽同位素的双 β 衰变的衰变常数来检验。梅耶夫人^[10]在理论上对这个过程做了研究，认为中微子和反中微子并不相同，而弗里^[11]的研究则认为马约拉纳^[12]的观点是正确的，即两类中微子是相同的。以钷-150的可能衰变表征双 β 衰变：

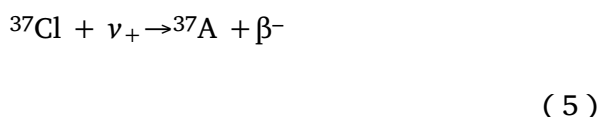
$$^{150}\text{Nd} \rightarrow ^{150}\text{Sm} + 2\beta^- + 2\nu_- \text{（狄拉克-梅耶夫人）} \quad (4a)$$

$$^{150}\text{Nd} \rightarrow ^{150}\text{Sm} + 2\beta^- \text{（马约拉纳-弗里）} \quad (4b)$$

如果中微子和反中微子是相同的，则一个中微子的虚发射和它立即被原子核重新吸收等效于两个中微子的实发射，可用式（4b）来表示。如果

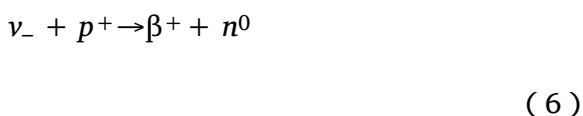
中微子和反中微子并不相同，便不可能存在这种抵消。对于式（4）所表达过程的半衰期，普里马科夫^[13]和科诺平斯基^[14]在两种情况下给出的结果完全不同，其中式（4a）的量级为 10^{19} 年，式（4b）的量级为 10^{15} 年，衰变可用的能量为5.4兆电子伏。此外，对于马约拉纳-弗里（式4b）的情况，可以预期得到两个 β 粒子总能量的线谱。 [英文](#)

一些屏蔽同位素表明，与式（4b）相一致的衰变周期并不存在^[15]。卡尔克施泰因和利比以及法尔曼和施瓦策先后在锡-124中发现了这一点，阿沙洛姆在钙-48中以及我们和我们的同事在铷-150中也发现了这一点。在钽-150的实验中，马约拉纳-弗里衰变的平均寿命下限被设置为 4×10^{18} 年（对应于背景中的一倍标准偏差）。这个极限可以与基于合理假设的值 1.3×10^{15} 年以及相同中微子情况下计算（用最严格的假设）的值 6×10^{17} 年进行比较。这个结论依旧认为中微子和反中微子是不同的粒子，只是至今尚未检测到它们之间的“差异”。戴维斯^[16]最近报道的实验负结果进一步支持了这个结论，他采用以下反应：



将1,000加仑的四氯化碳放置在大反应堆的附近作为氯靶，然后检验液体中是否存在氩-37。富含中子的裂变碎片应仅发射反中微子 ν_- 。 [英文](#)

根据 β 衰变过程各方面聚集的实验证据（除中微子外）的审慎推理可以支持存在中微子这一结论，而是否真实存在只能通过对中微子进行直接观测才能证明。如果中微子是一个真实的粒子，且携带 β 衰变位置处丢失的能量和动量，那么若在另一地点发现这些丢失的能量和动量便可以证明它真实存在。因此，如果式（1）中的负 β 衰变能与另一地点的下列逆反应（观测发现该逆反应以预期的速率发生）相关：



那么这个问题就解决了。已知自由中子 β 衰变的衰变常数和电子能谱，

将细致平衡原理应用于式（1），可以得到这个反应截面的表达式：

$$\sigma = \left(\frac{G^2}{2r}\right) \left(\frac{\hbar}{mc}\right)^2 \left(\frac{p}{mc}\right)^2 \left(\frac{1}{v/c}\right)^2 (\text{厘米}^2) \quad (7)$$

式中截面 σ 的单位为厘米²； G^2 （值为 44×10^{-24} ）是基于中子衰变^[9]的无量纲集总 β 耦合常数； p 、 m 和 v 分别是发射的正电子的动量、质量和速度， c 是光速， $2\pi\hbar$ 是普朗克常数，所有量都采用厘米·克·秒制单位。对于入射到自由质子上能量为3兆电子伏的中微子而言，这个截面是 10^{-43} 厘米²。式（6）中截面的精确解是中微子能量的函数：

$$\sigma = 1.0 \times 10^{-44} \times (E - a) \sqrt{(E - a)^2 - 1} (\text{厘米}^2) \quad (8)$$

式中 $a+1$ （值为3.53）是反应的阈值， E 是中微子能量，两者都以 $m_e c^2$ 为单位。束缚在核内的质子的阈值会随着靶与子核之间的能量差的增加而增高。有趣的是，我们注意到由式（8）可知，低能（ $E < a+1$ ）的中微子对物质的穿透力无限大，仅有几兆电子伏的中微子的穿透力都很大，测得的吸收平均自由程可与宇宙的半径相比。 [英文](#)

式（6）可以应用到如下实验：大量的氢原子作为强中微子流的靶，并用一个能够记录同时产生的正电子和中子的探测器进行监测。多兆瓦反应堆中的裂变碎片的高 β 衰变速率的可用性，以及通过使用液体闪烁器而带来的检测技术的改进，最终使得这类直接实验得以实施。对来自大反应堆的中微子流的估计表明，反应堆附近放置的50升水中每小时有几个质子发生反应（6）。问题是如何排除反应堆中的中子和 γ 射线、天然放射性和宇宙射线的背景的影响，合理有效地观测这些结果。1953年，我们^[17]在原子能委员会的汉福特场地进行的实验中，在这方面进行了尝试。我们用300升的液体闪烁器（内含甲苯和微量三联苯的混合物以及溶解了丙酸镅的 α -挥发油-苯基）提供靶质子。观测到脉冲对的延迟速率为每分钟 0.4 ± 0.2 个计数（每对的第一个可归为正电子，第二个可归为在镅中俘获的中子），该观测速率与预测速率相符，而且前面提到的背景影响也大大减小。然而，信号与整个背景的比仍然很低（1/20），因而进一步测试还不现实，结果也只是暂时性的。在汉福特经验的基础上，我们认为可以以一种确定的方式解决检测问题，综合考虑了进一步减小背景因素的目的之后，设计了第二个实验^[18]，该实验

可以独立检验式（6）中的每一项。 英文

图1是实验采用的检测方案的示意图。图示事件的发生顺序如下：从反应堆的裂变碎片中衰变得到的中微子使靶质子转变为中子，同时发射出一个正电子。正电子被靶水中的电子俘获，并发射两束0.51兆电子伏的湮没 γ 射线，被计数器I和II同时检测到。中子在几微秒内减速和扩散，最终被镉俘获并发射一些 γ 射线（总能量为9兆电子伏），这些射线再次被计数器I和II检测到。因此，我们得到一个瞬间符合，几微秒后，又得到第二个瞬间符合，从而形成了一个非常独特的事件序列。 英文

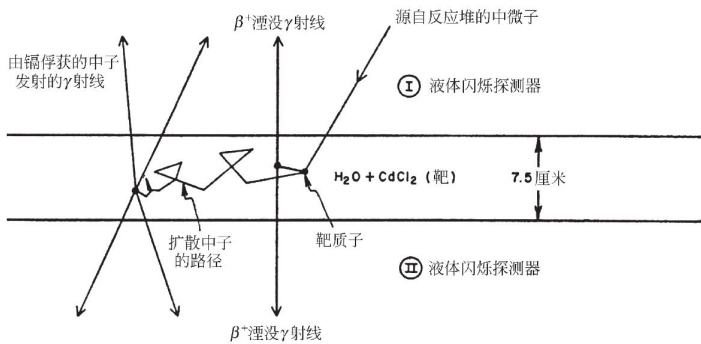


图1．中微子探测器示意图 英文

根据预测的每小时每升水中的事件数以及我们希望得到的探测效率来设置实验装置的总尺寸。设计几何形状和探测效率的一个主要影响因素是靶水本身对正电子湮灭辐射的吸收。实验和计算表明，水的最佳厚度为7.5厘米。由于整个效率需要约200升的靶以保证每小时产生几个计数，因此需要两个尺寸为1.9米×1.3米×0.07米的靶箱。液体闪烁探测器的深度（61厘米）可以保证高效率地吸收镉俘获的 γ 射线，并以最小的损耗传输 γ 射线产生的光到探测器终端。用110个5英寸的杜蒙特光电倍增管从每个探测箱的端部观察闪烁液体（三乙基苯、三联苯和POPOP波长变换剂），其中光电倍增管的数量主要取决于闪烁体中发射光子的数量。完整的检测器是一个“总汇三明治”式的组合，即在三个探测箱之间放置两个靶箱，从而构成了两个基本独立但共同使用中心探测箱的三件套。整个探测器装在一个铅-石蜡保护箱内，并放置在深层地下，位于美国原子能委员会的萨凡纳河工厂的一个生产堆附近。检测信号通过同轴电缆传输到位于反应堆建筑外的电子仪器拖车上。通过脉冲-高度

以及时间符合电路来分析脉冲，当接收到脉冲时，用照相方法将脉冲记录为三踪示波器上的径迹。图2是三件套底部一个事件的记录结果。用靶箱中的钷-钷中子源和溶解的铜-64正电子源校准整个系统；用标准化的脉冲发生器检测探测器以外的电子设备的稳定性。还通过探测器对宇宙射线中 μ 介子的响应检验它自身的性能。在运行1,371小时后（包括反应堆功率增长的时间和反应堆功率下降的时间），观测结果^[19]如下：

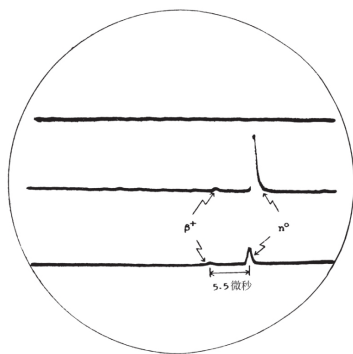


图2．一次特征记录。显示的四条示波器径迹分制对应三个探测箱。记录的这个事件发生在底部的三件套。在符合中首先见到的是每个探测箱中的“正电子”湮没 γ 射线脉冲，5.5微秒后，出现较大的“中子”脉冲。在这种情况下，选用能测量中子脉冲的放大倍数。并行运行的第二台示波器的放大倍数更大，用以测量正电子脉冲。 [英文](#)

（1）取决于反应堆功率的信号，为 2.88 ± 0.22 个计数/小时，是用超过20/1的信号-反应堆偶然背景比测量的，与预计^[20]的截面（ 6×10^{-44} 厘米²）相一致。信号-反应堆的独立背景比为3/1。 [英文](#)

（2）用重水稀释靶箱内的轻水溶液从而使质子密度为正常情况下一半，这样可使反应堆信号的速率下降到其以前的一半。而用钷-钷源测量的中子检测效率不变。 [英文](#)

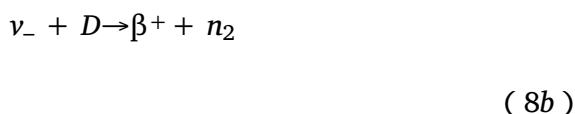
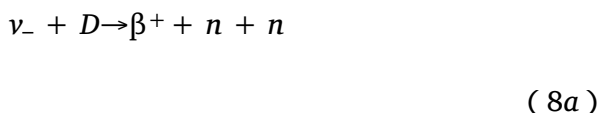
（3）通过一些实验表明，这对脉冲中的第一个脉冲是正电子湮没辐射形成的：其光谱与水中溶解的铜-64的正电子湮没辐射谱一致，并以预期的方式被插放在靶箱和探测器间的薄铅板吸收。 [英文](#)

（4）这对脉冲中的第二个脉冲是由与正电子同时产生的中子经延迟后在镅中俘获产生的，这可由其俘获时间分布与中子源的计算和观测结果相比较来确定。第二个脉冲的谱与镅俘获 γ 射线谱一致，移除镅将导致反应堆的信号也随之消失。 [英文](#)

(5) 对于与反应堆有关的辐射，例如中子和 γ 射线，有两类实验可将它们排除在信号来源之外。在第一类实验中，在检测器保护箱外放置一个强镅-铍中子源，我们发现它不仅在产生可接收的延迟符合方面效率很低，而且它产生的第一个脉冲谱并不像要求的信号那样随着能量的增高单调下降。在第二类实验中，一个附加的保护箱为反应堆的中子和 γ 射线提供了一个至少为10的衰减因子，观测发现除了影响到式(1)统计涨落外，它并不引起反应堆的信号变化。 [英文](#)

因此，对式(6)的逐项检测结果表明，在**高能裂变反应堆附近能观测到自由中微子**。 [英文](#)

来自反应堆的高通量中微子的可用性带来了许多有趣的可能性。其中一个源于前面提到的用重水稀释质子靶。这个试验是成立的，因为中微子与氘核相互作用的阈能比式(6)的阈能高2.2兆电子伏，这个值正是氘核的结合能，因此截面小一个量级；如果考虑到其他因素，其值可能还会进一步减小。然而中微子-氘的相互作用本身就很有意义，得到下面两个反应：



式中 n_2 是双中子^[21]的束缚态，不过目前尚未观测到。如果观测到反应(8a)发生，则精确测量其反应速率与式(6)反应速率之比，并应用裂变中微子谱的知识，将能直接测定在 β 衰变中费米常数与伽莫夫-特勒耦合常数的比值。这是因为：式(6)中的耦合常数包含上述两个常数，而式(8a)仅包含伽莫夫-特勒常数。另一方面，如果观测到式(8b)表示的反应，则不仅这些考虑成立，而且双中子束缚态（根据泡利不相容原理这个束缚态必然是一个单重态，即反平行自旋）的存在将直接影响到核力是否依赖于电荷这一问题。这是因为已经知道 (n, p) 体系的单重态是非束缚的。由于式(8a)中由裂变碎片中的中微子产生的

两个中子仅具有几千伏的能量，而且事件结束时它们处于自旋反平行态，因此条件似乎对双中子的形成十分有利，即使结合能仅几十千伏。

英文

自从泡利提出中微子假设并且在费米的核 β 衰变理论上取得成功
后，这种粒子已经被认为在观测到的许多不同介子^[22]的衰变中发挥着类似的作用。然而存在一个问题，即这些类中微子粒子与核子衰变的中微子是否是同一种粒子。我们注意到在核 β 衰变中，最初的核和最终的核均与原子核有明显的强相互作用。而在 (π,μ) 衰变中并不是这种情况，其中“中微子”的发射使重粒子与核的相互作用从强变弱。此外，尽管核 β 衰变矩阵元与那些 (μ,β) 衰变矩阵元明显相等，但是后者的最初产物和最终产物与核只有很弱的相互作用。

英文

人们曾认为，中微子是最小的物质实体；最大的是宇宙。试图用一事物来理解另一事物，就是希望横跨自然定律所有表现形式的尺度。然而，尽管现在我们对这些极限的知识还是模糊不清，但仍在试图通过想象解决这些问题。如果核反应在我们假定的宇宙的剧烈的诞生过程中发挥作用，那么有多少比重的初始能量快速地流入不可逆的中微子场中？这些中微子几乎从时间一开始就不与任何物质接触，那么它们会被宇宙普通的引力场捕获吗？如果答案是肯定的，那么它们现在的密度有多大，它们的能谱和角度分布又如何？中微子和反中微子以相等数量存在吗？如果中微子的静止质量为零，那么在讨论其引力势时，它是作为“物质”粒子还是电磁辐射来考虑？所有核能产生过程的宇宙最终产物的探测及其特性的测量，对当今的物理学无疑是一个重大的挑战。

英文

中微子的已知性质概括如下：

中微子的性质

自旋	$1/2 \hbar$
质量	即使有， $< 1/500$ 电子质量
电荷	0
磁矩	$< 10^{-9}$ 玻尔磁子
反应截面	在 3 兆电子伏时， $\nu + p^+ \rightarrow \beta^+ + n^0$ 截面为 10^{-43} 厘米 ² 。中微子 ν_e 与反中微子 $\bar{\nu}_e$ 不相同

英文

我们的工作以及本文中涉及的我们同事的工作得到美国原子能委员

会的支持。 英文

(沈乃澂 翻译；尚仁成 审稿)

Production of High Temperatures and Nuclear Reactions in a Gas Discharge

P. C. Thonemann *et al.*

The first hydrogen bomb, which derived energy from nuclear fusion rather than fission, was detonated in 1952. Two years later, physicists began trying to bring controlled nuclear fusion into the laboratory. Here Peter Thonemann and colleagues report on initial experiments with a device called the ZETA, a toroidal chamber 3 metres in diameter holding a dilute plasma. They were attempting to heat that plasma to temperatures approaching those in the Sun by using powerful bursts of current. The team describe encouraging initial results, but would later find that numerous plasma instabilities foiled the scheme's ultimate success. Today, more than 50 years later, a wide variety of plasma instabilities still put practical fusion energy out of reach.

[中文](#)

Introduction

THE basic conditions which must be established before a thermonuclear reactor is possible are, first, the containment of a high-temperature gas so that it is isolated from the walls of the surrounding vessel, and second, the attainment of temperatures sufficiently high for nuclear reactions to take place between the light elements. These

two conditions are interdependent. Poor containment results in energy losses so large that gas temperatures much exceeding 10^6 °K. are unattainable. [中文](#)

The experimental apparatus described was designed to study the containment of ionized hydrogen (or deuterium) by the magnetic field associated with the current flowing in the gas and to reach temperatures sufficiently high for nuclear reactions to be detectable using deuterium. This apparatus, known as ZETA, was built at the Atomic Energy Research Establishment Harwell. [中文](#)

The principles underlying the containment of a high-temperature gas by means of the “pinch effect” have been discussed by a number of authors¹⁻³. [中文](#)

The constricted gas discharge formed by passing a high current through a low-pressure gas, while isolating the gas from the tube walls for short periods of time, rapidly develops instabilities and distortions which lead to bombardment of the walls by electrons and positive ions. The consequent cooling and recombination make it impossible to maintain high temperatures except for a transient period⁴⁻⁸. These instabilities can be suppressed by the combination of an axial magnetic field parallel to the direction of the discharge current and by the fields produced by eddy currents induced in the surrounding metal walls when the current channel changes its position. [中文](#)

Theoretical studies of discharge stability in the presence of an axial magnetic field have been published⁹⁻¹², together with experimental evidence for stability in a straight discharge tube¹³. [中文](#)

The preliminary results reported in this article show that relatively long-time stability can be achieved in a toroidal metal-walled tube. The neutron yield and the kinetic ion temperatures have been measured over a limited range of conditions. The nuclear reaction-rates observed are not inconsistent with those expected from a

thermonuclear process.

中文

Apparatus

ZETA is a ring-shaped discharge tube of aluminium, 1-m. bore and 3-m. mean diameter, containing gas at low pressure. The gas, usually at a pressure of about 10^{-4} mm. of mercury, is made weakly conducting by a radio-frequency discharge. The toroidal ionized gas plasma forms the secondary of a large iron-cored pulse transformer. A condenser bank, storing up to a maximum of 5×10^5 joules, is discharged into the primary of the transformer, and produces a unidirectional current pulse in the gas up to a maximum of 200,000 amp. The current pulse in the gas lasts for about 4 msec. and is repeated every 10 sec. A steady axial magnetic field is generated by current-carrying coils wound on the torus. This field can be varied from zero to 400 gauss.

中文

Fig. 1 shows the discharge tube assembled with the transformer. A vacuum spectrograph can be seen connected to the torus body.

中

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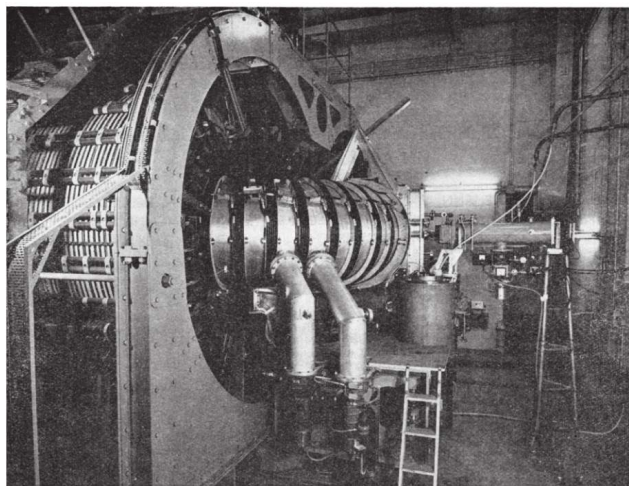


Fig. 1. Photograph of ZETA. The apparatus is enclosed in a room with concrete walls 3 ft. thick for radiation shielding

中文

Electrical Characteristics

Typical current and voltage oscillograms are shown in Fig. 2. The top trace is the “voltage per turn” measured by a loop around the iron core enclosed by the discharge tube. The length of the discharge path is approximately 1,000 cm. so that the initial electric field at the boundary of the ionized gas is about 2 V. per cm. The primary winding is short-circuited when the voltage per turn is zero, thus preventing the charge on the condensers reversing. The second trace shows the current flowing in the gas, which persists for about 2 msec. after the transformer primary is short-circuited.

中文

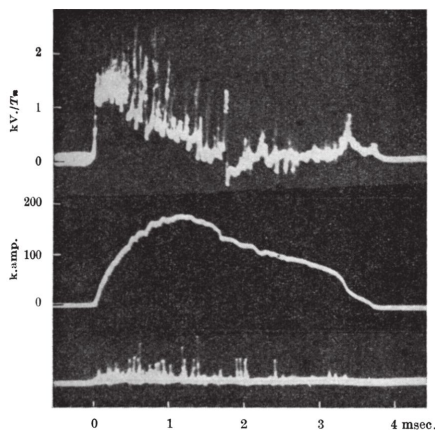


Fig. 2 Oscillograph recordings of the voltage per turn of the transformer, and the secondary current I_s . The lower trace shows the pulses produced by proton recoil in a scintillation neutron counter. Conditions: gas, deuterium + 5 percent nitrogen + 10 percent oxygen; pressure, 0.13×10^{-3} mm. mercury; axial field, 160 gauss

中文

As the current decreases the plasma expands until it reaches the walls. It is then cooled. A sudden increase in resistance accompanies this process and the consequent increase in $|dI/dt|$ produces a severe voltage transient which may rise to tens of kilovolts. Destructive voltage transients of this type are suppressed by the addition of 5 percent nitrogen without affecting the neutron yield.

中文

Stability

Measurements with magnetic field-probes and Langmuir probes, together with streak photographs of the current channel taken through a slit in the vacuum vessel, show the current channel to be quasi-stable and clear of the walls for the greater part of the current pulse. Fig. 3 is a reproduction of a streak picture of a helium discharge. The limit of the black area represents the internal diameter of the tube. The light recorded is that of the spark lines of impurities and of (He II) 4,686 Å. Streak pictures taken of discharges in deuterium are difficult to interpret as the light is emitted by neutral atoms and by impurity ions released into the current channel from the walls. [中文](#)

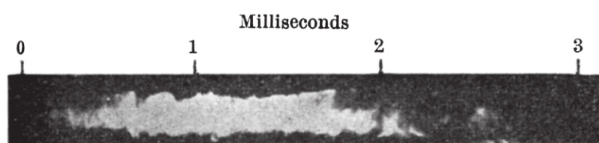


Fig. 3. Streak picture of a helium discharge. Conditions: initial gas pressure 0.25×10^{-3} mm. mercury; axial field 160 gauss; peak current, 130 k.amp. The tube walls lie at the boundary of the dark region [中文](#)

The centre of the current channel is displaced towards the outer wall due to the tendency of the ring current to expand. This expansion is opposed by eddy currents in the metal walls, which are of 1-in. thick aluminium. Measurements of the internal magnetic fields in the plasma are reproducible and show that the axial magnetic field, B_z , is trapped in the gas. On the axis it increases to approximately ten times the initial value. In general, the resultant lines of magnetic force due to the B_θ and B_z components are helical and vary in pitch over the cross-section of the plasma. The stability of a discharge with this magnetic-field configuration has not been treated theoretically. [中文](#)

The presence of the magnetic field-probe, which is 1 in. in diameter, greatly increases the discharge resistance and reduces the production of neutrons. [中文](#)

The diameter of the current channel estimated from the magnetic-field

measurements and the streak photographs is between 20 and 40 cm. at peak current. Transmission measurements with 4-mm. microwaves demonstrate that the electron density is greater than $6 \times 10^{13} \text{ cm}^{-3}$. This density is consistent with the assumption that all the gas present is ionized and contained in the current channel. 中文

High-Energy Radiations

Neutron emission arising from the D-D reaction is observed for gas currents in deuterium in excess of 84 k.amp. Emission occurs for a period of about 1 msec., centred about the peak current. 中文

Table 1 shows the average number of neutrons emitted per pulse as the peak current is increased. 中文

Table 1

Conditions: gas D₂ + 5 percent N₂. Pressure: 0.12×10^{-3} mm. B_z= 160 gauss

Current (k.amp.)	Total neutron yield per pulse	T _e (calc.)
84	0.4×10^4	2.4×10^4 °K.
117	3.1	2.9
126	9.2	3.3
135	14.2	3.6
141	26.5	3.8
150	41.6	4.0
177	108	4.5
178	125	4.6
187	134	4.65

中文

Fig. 4 is a histogram showing the average rate of neutron emission during the current pulse. 中文

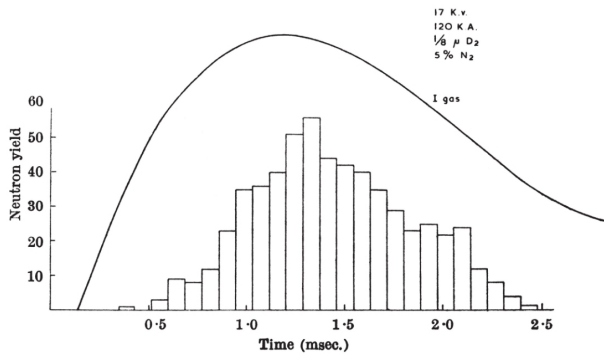


Fig. 4 Histogram showing the number of neutrons counted at various times during the current pulse [中文](#)

The third column of Table 1 gives the temperatures required to produce the observed neutron yields assuming a thermonuclear process. In calculating these figures, it has been assumed that the current channel is 20 cm. in diameter, emits neutrons uniformly for a period of 1 msec. and all the deuterium initially present is contained in the current channel. Since the reaction rate is an extremely sensitive function of temperature, variations in these parameters do not greatly affect the calculated temperature T_c . A comparison is made of the calculated and spectroscopically observed temperatures in Fig. 6. [中文](#)

Within the pressure-range investigated ($0.8\text{--}10.0 \times 10^{-4}$ mm.) the neutron yield decreased with increasing pressure. Neutrons were observed when 25 percent of the gas initially present was nitrogen, but the yield was much reduced. [中文](#)

The results obtained with a directional neutron counter moved around the torus showed that, within a factor of two, the neutron emission was uniform and did not arise from localized sources. [中文](#)

No correlation is found between the time of neutron emission and the voltage fluctuations during the current pulse. However, neutrons are produced at the large voltage transient at the end of the pulse, but these can be eliminated by the addition of nitrogen gas. [中文](#)

X-rays are observed towards the beginning of the current pulse. Their average energy lies in the range 20–30 kV. and on the average some 10^5 quanta per pulse are emitted by the whole tube. The number and energy of the X-ray quanta are insensitive to gas pressure and current, but increase in intensity as the axial magnetic field is increased. [中文](#)

Spectroscopic Observations

Both arc and spark line intensities vary greatly over the period of the pulse. In general, emission lines of normal atoms and ions up to three times ionized have a maximum intensity before peak current. Fig. 5 shows the intensity variation of (He II) 4,686 Å. and (O V) 2,781 Å.

中文

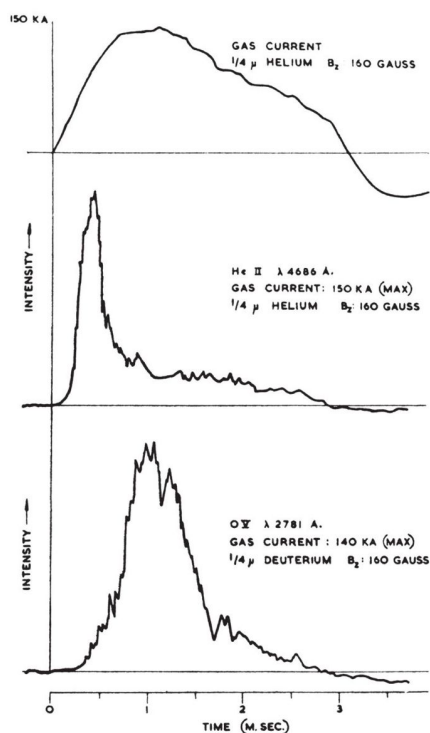


Fig. 5. The two lower traces are photomultiplier records of the intensity variation of two selected spark lines during the current pulse

中文

The Doppler broadening of spark lines emitted in a radial direction is used for estimating the kinetic ion temperature of deuterium and neon discharges. Small quantities of oxygen and nitrogen introduced into deuterium discharges provide spark lines in a convenient part of the spectrum. The breadth of the lines is of the order of 1 Å. and can be measured with a quartz spectrograph having a dispersion of 20 Å./mm. Calculations show that both Stark and Zeeman effects make a negligible contribution to the line-breadth. Mass motion may

contribute to the observed broadening to an appreciable extent, but both probe and streak records show no evidence of gross motion. The contribution to the line breadths of small-scale instabilities and turbulence remains to be measured. [中文](#)

Some 300 emission lines have been identified in the wave-length range 400–2,500 Å. The most prominent are those oxygen, nitrogen, aluminium and carbon. Strong lines of (O VI) are recorded. In this wave-length range more than 400 lines remain unidentified. [中文](#)

The (O V) line has been used for Doppler breadth determination without time resolution as it has a maximum intensity in the neighbourhood of peak current. For (N IV) 3,479 Å. this is not so, and light was admitted to the spectrograph for a period of 1 msec. centred about peak current. [中文](#)

The kinetic temperatures obtained by observation of (O V) and (N IV) lines as a function of peak current are shown in Fig. 6. The ion temperatures are found to decrease with increasing initial pressure of deuterium. No satisfactory measurement of electron temperature has yet been made. [中文](#)

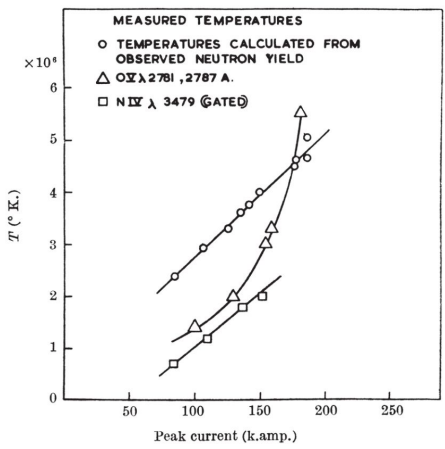


Fig. 6. Ion temperature as a function of peak current determined from the Doppler broadening of (O V) and (N IV). Conditions: initial gas pressure, 0.13×10^{-3} mm. deuterium and 5 percent nitrogen; $B_z = 160$ gauss. The temperature of the deuterium gas, estimated from the observed neutron yield, is shown for comparison [中文](#)

Conclusion

These preliminary results demonstrate that it is possible to produce a stable highly ionized plasma isolated from the walls of a toroidal tube. Hydrogen gas has been maintained in a state of virtually complete ionization with a particle density lying between 10^{13} and 10^{14} per cm^3 , for times of milliseconds. The mean energy of the ions in the plasma is certainly of the order of 300 eV., and there are many indications that the electron temperature is of the same order. The containment time and the high electrical conductivity are both adequate for the detailed study of magnetohydrodynamical processes.

[中文](#)

To identify a thermonuclear process it is necessary to show that random collisions in the gas between deuterium ions are responsible for the nuclear reactions. In principle, this can be done by calculating the velocity distribution of the reacting deuterium ions from an exact determination of both the energy and direction of emission of the neutrons. The neutron flux so far obtained is insufficient to attain the desired accuracy of measurement. [中文](#)

Investigations leading up to the present results have been constantly encouraged and supported by Sir John Cockcroft and the late Lord Cherwell. The theoretical investigations have been directed by Dr. W. B. Thompson, of the Theoretical Physics Division. [中文](#)

A major part of the engineering design and construction of ZETA was done by the Metropolitan-Vickers Electrical Co., Ltd. [中文](#)

(181, 217-220; 1958)

P. C. Thonemann, E. P. Butt, R. Carruthers, A. N. Dellis, D. W. Fry, A. Gibson, G. N. Harding, D. J. Lees, R. W. P. McWhirter, R. S. Pease, S. A. Ramsden and S. Ward: Atomic Energy Research Establishment, Harwell.

References:

1. Post, B. F., *Rev. Mod. Phys.*, **28**, 338 (1956).
 2. Pease, R. S., *Proc. Phys. Soc.*, B, **70**, 11 (1957).
 3. Burkhart, L. C., Dunaway, B. E., Mather, J. W., Phillips, J. A., Sawyer, G. A., Stratton, T. F., Stovall, E. J., and Tuck, J. L., *J. App. Phys.*, **28**, 519 (1957).
 4. Kurchatov, I. V., *Atomnaya Energiya*, **1**, No. 3, 65 (1956). English translation, *J. Nuclear Energy*, **4**, 198 (1957).
 5. Artaimovitch, L. A., Andrianov, A. M., Bazilevakaya, O. A., Prokhorov, YU. G. and Filippov, N. V., *Atomnaya Energiya*, **1**, No. 3, 76 (1956). English translation, *J. Nuclear Energy*, **4**, 203 (1957).
 6. Colgate, S.
 7. Berglund, S., Nilsson, R., Ohlin, P., Siegbahn, K., Sundstrom, T., and
Svennerstedt, S., *Nuclear Instruments*, **1**, 233 (1957).
 8. Curran, S., and Allen, K. W.
- $\left. \begin{array}{l} \\ \\ \end{array} \right\} \text{Proc. 3rd Int. Conf. on Ionization Phenomena in Gases, Venice (1957).}$
9. Shrafranov, V. D., *Atomnaya Energiya*, **1**, No. 5, 38 (1956). English translation, *J. Nuclear Energy*, **5**, 86 (1957).
 10. Tayler, R. J., *Proc. Phys. Soc.*, B, **70**, 1049 (1957).
 11. Bosenbluth, M.
 12. Bickerton, R. J.
- $\left. \begin{array}{l} \\ \\ \end{array} \right\} \text{Proc. 3rd Int. Conf. on Ionization Phenomena in Gases, Venice (1957).}$
13. Bezba chenko, A. L., Golovin, I. N., Ivanov D. P., Kirillov, V. D., Yavlinsky, N. A., *Atomnaya Energiya*, **1**, No. 5, 26 (1956). English translation, *J. Nuclear Energy*, **5**, 71 (1957).

气体放电中产生的高温和核反应

索恩曼等

1952年第一颗氢弹爆炸，其能量来自核聚变而不是核裂变。两年后，物理学家开始尝试将可控的核聚变引入实验室。本文中彼得·索恩曼及其同事报道了最初的实验，在实验中他们使用一个叫ZETA的装置，这个装置是一个直径为3米并装有稀薄等离子体的环形腔。他们试图通过强大的电流爆发加热等离子体使其温度接近太阳的温度。这个小组描述了令人振奋的初步结果，但不久发现大量的等离子体的不稳定性阻碍了课题的最终成功。五十多年后的今天，多种等离子体的不稳定性仍然阻碍着聚变能的应用。

[英文](#)

引言

在成功建立热核反应堆前必须具备的基本条件是：第一，约束高温气体，确保将其与周围的容器壁隔离开；第二，达到足够高的温度，使轻元素间能发生核反应。这两个条件是相互依存的。不好的约束条件会使能量损失太大，以致气体温度难以达到远大于 10^6 K的温度。

[英文](#)

设计的实验装置通过与气体中电流相关的磁场来研究电离氢（或氘）的约束情况，该装置能达到可以用氘检测是否发生核反应所需的足够高的温度。这台在哈威尔原子能研究中心建立的装置被称为ZETA。

[英文](#)

许多作者^[1-3]已讨论了用“箍缩效应”方法约束高温气体的原理。

[英文](#)

短时间内将气体与管壁隔离开时，在低压气体中通过强电流产生的

压缩气体放电会很快变得不稳定并发生变形，这会导致电子或正离子轰击壁。除非在过渡周期^[4-8]，否则随后的冷却和复合将使等离子体不可能保持高温。这些不稳定性可以通过平行于放电电流方向的轴向磁场的叠加和电流通道改变位置时在周围金属壁感生的涡旋电流产生的磁场来加以抑制。 [英文](#)

轴向磁场存在时放电稳定度的理论研究^[9-12]，以及在直线放电管中稳定性的实验证据^[13]现已发表。 [英文](#)

本文中报道的初步结果表明，在环形的金属壁管中能够实现较长时间的稳定。在有限范围的条件下，已测量了中子产生和离子动力学温度。观测到的核反应速率并没有与热核过程预期的结果相矛盾。 [英文](#)

装置

ZETA是一个铝的环形放电管，管径为1米，平均直径为3米，内装有低压气体。通常气体的压强约为 10^{-4} 毫米汞柱，射频放电使其具有弱的导电性。环形电离的气体等离子体形成了一个大铁芯的脉冲变压器的次级。电容器储备了最大为 5×10^5 焦的能量，它放电到变压器的初级，在气体中产生一个单向的最大值为200,000安的电流脉冲。在气体中的电流脉冲持续约4毫秒，每10秒重复一次。稳定的轴向磁场是由绕在环上的载流线圈产生的。磁场从0变到400高斯。 [英文](#)

图1显示了装有变压器的放电管。可以看到环流器主体与一台真空光谱仪连接。 [英文](#)

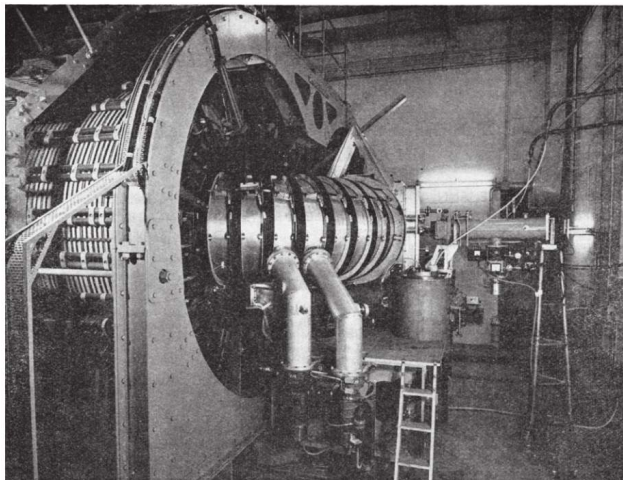


图1 . ZETA的照片。为了屏蔽辐射，装置密封在3英尺厚的混凝土墙的室内。

英文

电学特性

图2是电流和电压的特征波形图。上面的轨迹是用放电管包围的铁芯环绕的回路测量的“每匝的电压”。放电路程的长度近似为1,000厘米，因此，在电离气体边界的初始电场约为2伏/厘米。当每匝的电压为零时，初级线圈被短路，因此避免了电容器的电荷反向。第二个轨迹显示了气体中的电流，它在变压器初级线圈短路后持续约2毫秒。

英文

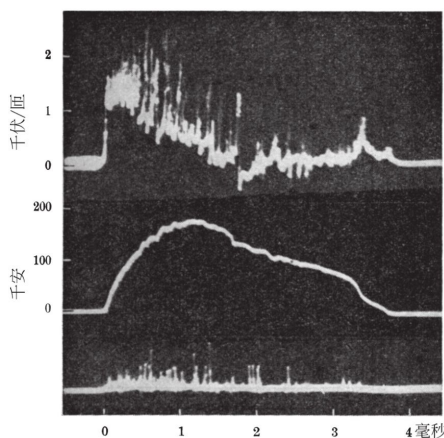


图2 . 示波器记录的变压器每匝电压以及次级电流 I_{so} 。下方的径迹显示的是在闪烁中子计数器中质子反冲产生的脉冲。条件：气体，氘+5%氮+10%氧；气压， 0.13×10^{-3} 毫米汞柱；轴向场为160高斯。

英文

当电流减小时，等离子体扩展直到它到达器壁，然后冷却。伴随这一过程，电阻突然增大， $|dI/dt|$ 相继增大，产生瞬间急剧增长的电压，

它可以增高到几十千伏。通过附加不影响中子产生的5%的氮可抑制这类破坏性电压瞬变。 [英文](#)

稳定度

由磁场探针和朗缪尔探针进行的测量与通过真空容器的狭缝拍摄的电流通道的条纹照片一起可知，电流通道是准稳定的并且显示大部分的电流脉冲没有接触管壁。图3是氦放电的条纹图的重现。黑色区域的边界代表了管的内径。记录的光是杂质和4,686埃（HeII）的火花放电谱线。氦放电的条纹图难以解释为光是由中性原子和从器壁进入电流通道的杂质离子所发射的。 [英文](#)

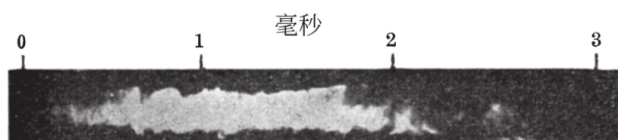


图3．氦放电的条纹图。条件：初始气压为 0.25×10^{-3} 毫米汞柱；轴向磁场为160高斯；峰值电流为130千安。管壁位于黑色区边缘。 [英文](#)

电流通道的中心会由于环形电流扩张的趋势而移向外壁。这种扩张受到1英寸厚铝金属壁中涡旋电流的抵制。等离子体内的磁场测量是可重复的，测量还显示轴向磁场 B_z 局限于气体中。在轴上，它增大到约初始值的十倍。通常由 B_0 和 B_z 分量产生的磁力线是螺旋形的，螺旋间距随等离子体截面变化。理论上尚未对具有这类形状的磁场的放电稳定度做过处理。 [英文](#)

磁场探针直径为1英寸，极大地增加了放电电阻并减少了中子的产生。 [英文](#)

从磁场测量和条纹照片估计的电流通道在峰值电流处的直径在20厘米~40厘米之间。通过使用4毫米微波的透射测量表明，电子密度大于 6×10^{13} 厘米⁻³。这个密度与所有气体是电离的并包含在电流通道中的假设一致。 [英文](#)

高能辐射

在氘的气体电流超过84千安时观测D-D反应产生的中子发射，发现发射集中在峰值电流附近，时间约为1毫秒。[英文](#)

表1显示了在峰值电流增高时每个脉冲发射的平均中子数。[英文](#)

表1

条件：气体 $D_2+5\% N_2$ ；气压： 0.12×10^{-3} 毫米汞柱； $B_2 = 160$ 高斯

电流 (千安)	每个脉冲产生的总中子数	T_c (计算值)
84	0.4×10^4	2.4×10^4 K
117	3.1	2.9
126	9.2	3.3
135	14.2	3.6
141	26.5	3.8
150	41.6	4.0
177	108	4.5
178	125	4.6
187	134	4.65

[英文](#)

图4为在电流脉冲周期内中子发射的平均速率的直方图。[英文](#)

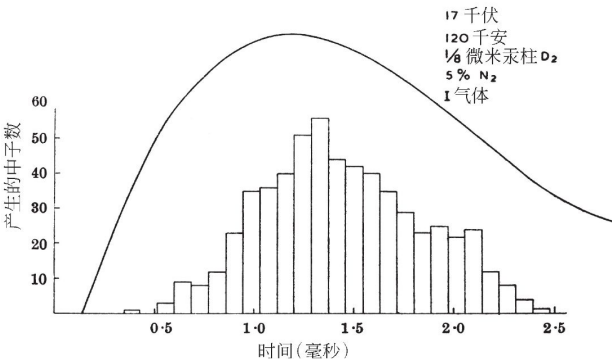


图4．电流脉冲周期内不同时间的中子计数的直方图 [英文](#)

表1的第三列给出了假定的热核过程产生观测到的中子数所需的温度。在计算这些值时假定，电流通道的直径是20厘米，在1毫秒期间内均匀地发射中子，并且所有最初存在的氘均在电流通道内。由于反应速率是一个对温度极其灵敏的函数，这些参量的变化并不会对计算的温度 T_c 产生很大的影响。在图6中对计算的温度与光谱仪上观测到的温度做了对比。[英文](#)

在所研究的气压范围内 (0.8×10^{-4} 毫米汞柱~ 10.0×10^{-4} 毫米汞

柱)，随着压强增高，产生的中子将会减少。最初存在的气体中25%是氮气时，观测到了中子，但中子产额大大减少。 [英文](#)

用沿环流器运动的定向中子计数器得到的结果表明，在最大值与最小值相差不到两倍的意义上，中子发射是均匀的，并不是由局域源产生的。 [英文](#)

在中子发射时间和电流脉冲期间的电压起伏之间并没有发现相关性。然而，中子是在脉冲末端的大电压瞬态时产生的，但这可以通过添加氮气来消除。 [英文](#)

在电流脉冲起始时观测到X射线，其平均能量在20千伏~30千伏范围内，整个管平均每个脉冲发射 10^5 个量子。X射线量子的数量和能量对于气压和电流并不敏感，但是强度随轴向磁场的增大而增强。 [英文](#)

光谱观测

弧光和火花放电谱线的强度在脉冲周期内变化都很大。通常正常的原子和三次电离的离子的发射谱线在峰值电流前有一个最大强度。图5显示了4,686埃（He II）和2,781埃（O V）的谱线强度变化。 [英文](#)

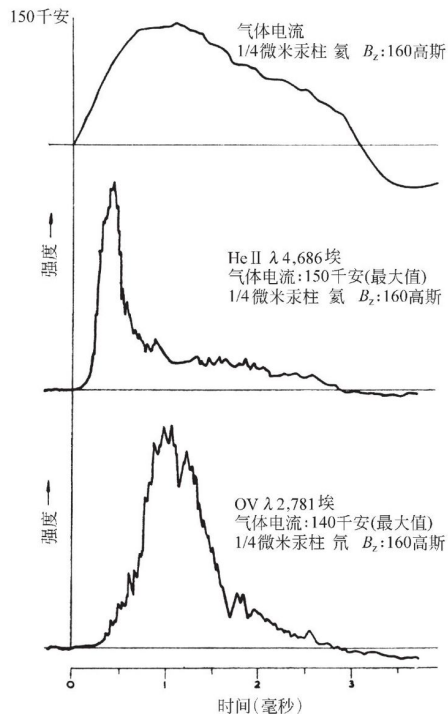


图5. 图中下方的两条径迹是光电倍增管记录的在电流脉冲期间选择的火花放电的两个谱线强度的变化 [英文](#)

径向发射的火花放电谱线的多普勒展宽可用来估计氦和氖放电的运动学离子温度。引入到氖放电中的少量氧和氮，在谱线适当部分提供火花放电谱线。谱线宽度是1埃的量级，可以用色散为20埃/毫米的石英光谱仪测量。计算表明，斯塔克效应和塞曼效应对线宽的影响可忽略不计。集体运动可能有助于谱线增宽变显著，但探针和条纹记录均没有证据显示总体运动。小范围的不稳定性及扰动对谱线宽度的影响尚有待测量。 [英文](#)

在波长为400埃~2,500埃的范围内，约300条发射谱线已被确认。最显著的是氧、氮、铝和碳的发射谱线。其中，记录了(O VI)的强谱线。在这个波长区间内，还有400多条谱线有待确认。 [英文](#)

由于(O V)谱线在峰值电流附近有最大的强度，它已被用于测定无时间分辨的多普勒宽度。(N IV) 3,479埃并不是这样，光在峰值电流中心1毫秒范围内被放入到光谱仪中。 [英文](#)

图6显示了根据（O V）和（N IV）谱线的观测得出的动力学温度，它是峰值电流的函数。发现离子温度随氘的最初压强的增高而降低。对电子温度尚未得到满意的测量结果。 [英文](#)

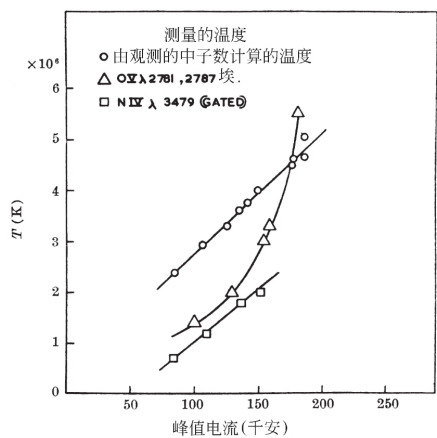


图6. 根据（O V）和（N IV）的多普勒展宽确定的离子温度作为峰值电流的函数。条件：最初气压为 0.13×10^{-3} 毫米汞柱的氘和5%的氮； $B_z = 160$ 高斯。作为对比，图中还给出了根据观测的中子产生估计的氘气体的温度。 [英文](#)

结论

这些初步结果表明，可以产生与螺旋管壁隔离的稳定的高度电离等离子体。在几毫秒时间内，氢气体维持完全电离的状态，其粒子密度在每立方厘米 10^{13} 至 10^{14} 之间。等离子体内的离子平均能量量级为300电子伏，许多事实表明，电子的温度处于相同量级。约束时间和高电导对于详尽研究磁流体力学过程都是合适的。 [英文](#)

为了确认热核过程，必须说明核反应是由气体中氘离子之间随机碰撞引起的。原则上，这一点可以通过计算反应氘粒子的速率分布得到，速率分布又可以通过中子能量和发射方向的精确测定而得到。至今得出的中子通量还不足以获得所要求的测量精确度。 [英文](#)

为获得现有结果所做的研究得到了约翰·考克饶夫爵士和已故的彻韦尔勋爵不断的鼓励和支持。理论研究得到了理论物理部的汤普森博士的指导。 [英文](#)

工程设计的主要部分和ZETA的构建是由茂伟电气公司完成的。

(沈乃澂 翻译；尚仁成 审稿)

Co-operative Phenomena in Hot Plasmas

L. Spitzer, jun.

The new experiments producing high-temperature plasmas in the ZETA device at Harwell not only shed light on the potential for controlled fusion energy, but also provided an opportunity for studying plasma physics in extreme conditions. Here physicist Lyman Spitzer reports on a mystery evident in the ZETA data: an anomalously fast rise in the temperature of positive ions, which in theory should gain energy more slowly through collisions with hot electrons. These findings indicated that physicists still had much to learn about the rich dynamics within plasmas, and the many collective instabilities which drive it. This theme of the overwhelming collective complexity of dynamical behaviour would be a common one in plasma physics for the next half century. [中文](#)

THE interesting results described by Thonemann and his co-workers in the preceding article provide not only an important step forward in the controlled release of thermonuclear energy, but also a challenging problem in the dynamics of fully ionized gases or plasmas. The spectroscopic line profiles and the neutron counts provide incontrovertible evidence for the acceleration of the positive ions. However, theory would seem to indicate that electron-ion collisions are inadequate to explain the observed rate of heating, and some

unknown mechanism would appear to be involved. [中文](#)

The rate at which the positive-ion temperature increases, as a result of electron-ion collisions, has been given elsewhere¹. It has been suggested, both in Great Britain and in the United States, that this process might be inadequate to explain the rate at which positive ions gain energy in certain electrical discharges. A relatively simple procedure, due to Stix², may be used to set an upper limit to the rate at which positive ions are heated by electron-ion collisions. In this method the rate of heating is made a maximum by setting the electron temperature equal to three times the ion temperature, T_i , and setting the electron density equal to a constant, n_e , corresponding to complete ionization and concentration within the discharge channel of all the gas initially present in the tube. On this basis (with $\ln\Lambda$ set equal to 15, see ref. 1) T_i is given by the relation

$$T_i^{3/2} = 1.71 \times 10^{-2} n_e t \tag{1}$$

where T_i is in degrees K., n_e in electrons per cm.³, and t in seconds.

[中文](#)

To determine the density in the ZETA experiments, we compute the radius, r_d , of the discharge channel on the assumption that the flux of the axial magnetic field, B_z , is held constant in the gas during the contraction, and that the field, B_θ , due to the current equals the compressed axial field at the boundary of the discharge. As a result of the high temperatures achieved in ZETA, appreciable leakage of axial flux out of the discharge does not appear to be possible. Neglect of the finite gas pressure decreases the computed channel radius, increases n_e and again makes the rate of increase of T_i a maximum. On these assumptions, values of r_d have been computed for two currents, and an initial B_z of 160 gauss, and are listed in the second column of Table

1. [中文](#)

Table 1

I (amp.)	r_d (cm.)	n_e (cm. ⁻³)	T_i (°K.)	t (theor.)	t (obs.)
126,000	16	8.6×10^{13}	3.3×10^5	4.0×10^{-3}	1.0×10^{-3}
140,000	14	1.1×10^{14}	2.5×10^5	2.0×10^{-3}	1.0×10^{-3}

中文

These values of r_d are consistent with those cited by the Harwell group. The values of n_e in the third column correspond to complete ionization of all the deuterium initially present in the torus, at a pressure of $1/8\mu$, and its concentration in the current channel. The value of T_i for the lower current in column 4 is taken from Table 1 in the article by Thonemann *et al.*, and is based on the neutron yield. The value of T_i at the higher current is the temperature obtained from the Doppler width of the O V triplet, as shown in Fig. 6 of the Harwell article. The ion temperature obtained from the neutron yield under this condition is about 50 percent greater, but no information is available on the time at which the neutrons appear in this case. In the fifth column are given the values of the time, in seconds, required for the positive ions to reach this temperature, computed from equation 1.

中文

For comparison, the final column lists the observed times, in seconds, at which the positive-ion energies reach the values corresponding to the fourth column. For the lesser current, this is the time at which the neutron yield reaches half its peak value as shown in Fig. 4 of the paper from Harwell. For the greater value of current, t (obs.) is set equal to the time at which the O V radiation reaches its peak intensity, as shown in Fig. 5 of the Harwell paper. The simplifications made have tended to reduce t (theor.), and the correct value may be about an order of magnitude greater than given in Table 1. Thus the discrepancy seems real. There does not appear to be any simple model, based on a quiescent plasma, which is consistent with the observed rapid heating of the positive ions.

中文

Following a suggestion by the Harwell group as to the importance of

non-thermal heating processes, Stix² in 1956 arrived at conclusions similar to the above from experimental results obtained at Project Matterhorn. A discharge was produced in helium gas in a stainless-steel race-track tube of 10 cm. diameter and 240 cm. axial length, with an initial pressure of 0.63μ and an externally produced axial field of 19,000 gauss. The magnetic field was arranged so that intersection of the outer lines of force with material walls restricted the discharge to a channel of 5 cm. diameter. A loop voltage of 300 V. was applied around an iron transformer threading the race-track, and a maximum current of 8,000 amp. observed; since this current produces only a minor perturbation in the magnetic field, there was no pinching of the discharge. Time-resolved spectroscopic profiles of the He II line, λ 4,686, indicated that the kinetic temperature of these ions increased to 1.2×10^6 degrees K. in 1.5×10^{-4} sec., as compared to a theoretical maximum value of 0.8×10^6 degrees in this same time-interval. 中文

文

It has been known since the work by Langmuir³ that electrons in a conventional gas discharge approach a Maxwellian distribution much more rapidly than can be explained by inter-particle collisions. Recent research by Gabor and his collaborators⁴ has shown that oscillations generated in the plasma sheath are responsible for much of this effect, but the detailed mechanism is still unexplained. Possibly the high ion energies observed in ZETA represent a phenomenon related to Langmuir's paradox. To analyse the possible processes involved, such as oscillations, shocks, hydromagnetic turbulences, etc., it would be helpful to obtain information on the extent to which the positive-ion velocities are thermalized, that is, on how nearly the distribution function is isotropic and Maxwellian. Evidently detailed experimental investigations of these cooperative effects in hot plasmas will be of great interest in basic physics. 中文

References:

1. Spitzer, L., "Physics of Fully Ionized Gases" (Interscience Publishers, 1956, Section 5.3).
2. Stix, T., Talk at Berkeley, California (February 20-23, 1957).
3. Langmuir, I., *Phys. Rev.*, **26**, 585 (1925); *Z. Phys.*, **46**, 271 (1928).
4. Gabor, D., Ash, E. A., and Dracott, D., *Nature*, **176**, 916 (1955).

热等离子体中的协同现象

小斯皮策

在哈佛的ZETA设备上产生高温等离子体的新实验不仅为可控核聚变的研究带来一线光明，同时也为我们提供了一个研究极端条件下等离子体物理的机会。本文中物理学家赖曼·斯皮策指出了ZETA数据中一个谜团：正离子温度异常地快速上升，而理论上来说，由于它与热电子相互碰撞，因此获得能量的速率应该更加缓慢。这些发现说明，物理学家们对于等离子体内丰富的动力学现象以及导致这种现象的众多集体不稳定性仍需进一步的探索。在此后的半个世纪的时间里，动力学行为这个错综复杂且极具挑战性的问题成为等离子体物理中一个很常见的研究主题。 [英文](#)

索恩曼及其同事们在先前的文章中阐述了一个很有意思的结果，这个结果不仅说明我们在热核能量的可控释放中迈出了重要的一步，而且还提出了一个极具挑战性的有关完全电离的气体（即等离子体）的动力学问题。光谱线剖面和中子数提供了与正离子加速相矛盾的证据。然而，理论显示仅靠电子-离子碰撞并不足以解释观测到的升温速率，其中应该包含某些未知的机制。 [英文](#)

在之前的一篇文章^[1]中，我曾提到正离子温度升高的速率是由电子-离子碰撞导致的。然而在英国和美国都有人提出，这个碰撞过程不足以解释正离子在释放电荷后获得能量的速率。斯蒂克斯^[2]提出了一个相对简单的过程，可以用来确定电子-离子碰撞所导致的正离子升温的速率上限。在这种方法中，将电子温度取为离子温度 T_i 的三倍，设定电子密度为一常数 n_e ，相当于完全电离并且管内最初存在的所有气体都浓缩在放电通道内，在这些条件下可以得到加热速率的最大值。据此（ $\ln \Lambda$ 取为15，见参考文献1）， T_i 由下列关系式给出：

$$T_i^{3/2} = 1.71 \times 10^{-2} n_e t$$
(1)

式中， T_i 的单位是K， n_e 的单位是每立方厘米的电子数， t 的单位是秒。

英文

为了测定ZETA实验中的密度，我们在下面两个假设的基础上计算了放电通道的半径 r_d 。一是假定在收缩过程中轴向磁场 B_z 方向上的通量保持不变，二是假定由电流产生的磁场 B_0 等于放电界面上被压缩的轴向磁场。由于ZETA实现了高温，因此基本不会出现放电造成的轴向磁通量的明显泄漏。忽略有限的气压使得计算出的通道半径变小，并使 n_e 增大，最后使 T_i 的增长率达到最大值。基于这些假设，对两个电流强度下的 r_d 值进行计算，最初的 B_z 为160高斯，计算结果详见表1的第二列。

英文

表1

I (安)	r_e (厘米)	n_e (厘米 ⁻³)	T_i (K)	t (理论值)	t (观测值)
126,000	16	8.6×10^{13}	3.3×10^6	4.0×10^{-3}	1.0×10^{-3}
140,000	14	1.1×10^{14}	2.5×10^6	2.0×10^{-3}	1.0×10^{-3}

英文

这些 r_d 的值与哈威尔小组引用的数值是一致的。在第三列中 n_e 的值对应的是最初存在于环内的所有氙在气压为1/8微米汞柱时完全电离并浓缩在电流通道内的情况。第四列中较低电流下的 T_i 值取自索恩曼等人的论文中的表1，它是根据中子产额而得出的。较高电流下的 T_i 值是根据哈威尔小组的论文中图6所示的O V三重线的多普勒宽度而得出的。在这种条件下，根据中子产额得到的离子温度升高了约50%，但还无法确定在这种情况下中子是什么时候开始产生的。在第五列中给出了以秒为单位的时间的值，这是根据式（1）计算出的正离子达到这个温度所需要的时间。

英文

为了进行比较，最后一列给出了以秒为单位的观测时间，在这个时间内正离子能量达到第四列的温度所对应的值。对于较小电流的情况，这是中子产额达到其峰值一半时所用的时间，如哈威尔小组的论文中图4所示。对于较大电流的情况， t （观测值）取O V辐射值达到其峰值强度时所用的时间，如哈威尔小组的论文中图5所示。这种简化常常使得

t (理论值) 偏小, 修正值可能会比表1给出的值大约大一个数量级。因此差异看起来确实存在。似乎并没有能和观测到的阳离子的快速加热相吻合的基于静等离子体的任何简单模型。 [英文](#)

1956年, 按哈威尔小组关于非热效应的加热过程的重要性所提出的建议, 斯蒂克斯^[2]得到了与马特峰计划的实验结果相类似的结论。在直径10厘米、轴长240厘米充满氦气的不锈钢环形管中进行放电, 其初始气压为0.63微米汞柱, 外部产生的轴向磁场为19,000高斯。磁场的分布使得外部的磁力线与材料壁交叉从而将放电限制在直径为5厘米的通道内。将300伏回路电压加在穿过粒子轨道的铁变压器周围, 观测到的最大电流为8,000安; 因为电流在磁场中只产生了较小的扰动, 所以并不存在放电的箍缩。 λ 为4,686埃的氦II线的时间分辨光谱图表明, 这些离子的动力学温度在 1.5×10^{-4} 秒内增高到 1.2×10^6 K, 而理论上在这一时间内所能达到的最大值是 0.8×10^6 K。 [英文](#)

依据朗缪尔^[3]的工作我们知道, 在传统的气体放电中, 电子以极快的速率达到麦克斯韦分布而单纯用粒子间的相互碰撞无法对此进行解释。最近盖伯及其同事们^[4]的研究表明, 这种效应主要是由等离子体鞘层中产生的振荡造成的, 但具体的机制还无法解释。在ZETA中观测到的高离子能也许代表了一种与朗缪尔悖论相关的现象。为了分析可能包含的过程 (例如振荡、冲击、磁流体湍流等), 有必要收集与正离子速度被热能化的程度有关的信息, 即分布函数在多大程度上接近于各向同性和麦克斯韦分布。显然, 对热等离子体中协同效应的详细情况的实验研究, 将是基础物理学科中一个非常有趣的课题。 [英文](#)

(沈乃澍 翻译; 尚仁成 审稿)

Stimulated Optical Radiation in Ruby

T. H. Maiman

Albert Einstein identified the phenomenon of the stimulated emission of radiation early in the 20th century—how radiation of a particular frequency could stimulate more of the same to be emitted in an excited medium. Here Theodore Maiman of the Hughes Research Laboratories in California reported the first observation of the effect in a cube of ruby with ends coated with reflective silver. These mirrors create an “optical cavity” within which light bounces back and forth to stimulate emission from chromium ions in an electronically excited state. This “light amplification by stimulated emission of radiation” was the first basic demonstration of the principles of laser action. [中文](#)

SCHAWLOW and Townes¹ have proposed a technique for the generation of very monochromatic radiation in the infra-red optical region of the spectrum using an alkali vapour as the active medium. Javan² and Sanders³ have discussed proposals involving electron-excited gaseous systems. In this laboratory an optical pumping technique has been successfully applied to a fluorescent solid resulting in the attainment of negative temperatures and stimulated optical emission at a wave-length of $6,943 \text{ \AA}$; the active material used was ruby (chromium in corundum). [中文](#)

A simplified energy-level diagram for triply ionized chromium in this crystal is shown in Fig. 1. When this material is irradiated with energy at a wave-length of about 5,500 Å., chromium ions are excited to the $4F_2$ state and then quickly lose some of their excitation energy through non-radiative transitions to the $2E$ state⁴. This state then slowly decays by spontaneously emitting a sharp doublet the components of which at 300°K. are at 6,943 Å. and 6,929 Å.(Fig. 2a). Under very intense excitation the population of this metastable state ($2E$) can become greater than that of the ground-state; this is the condition for negative temperatures and consequently amplification via stimulated emission.

中文

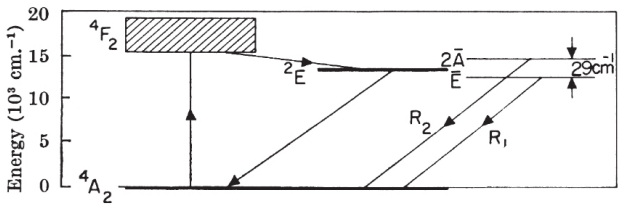


Fig. 1. Energy-level diagram of Cr^{3+} in corundum, showing pertinent processes

中文

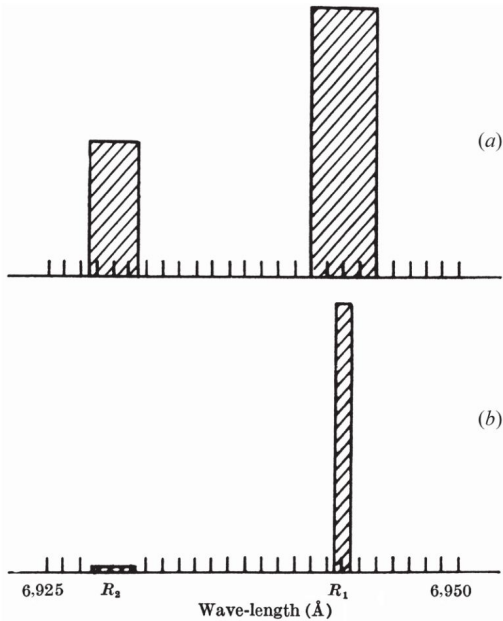


Fig. 2. Emission spectrum of ruby: a, low-power excitation; b, high-power excitation

中文

To demonstrate the above effect a ruby crystal of 1-cm. dimensions coated on two parallel faces with silver was irradiated by a high-power flash lamp; the emission spectrum obtained under these conditions is shown in Fig. 2b. These results can be explained on the basis that negative temperatures were produced and regenerative amplification ensued. I expect, in principle, a considerably greater ($\sim 10^8$) reduction in line width when mode selection techniques are used¹. 中文

I gratefully acknowledge helpful discussions with G. Birnbaum, R. W. Hellwarth, L. C. Levitt, and R. A. Satten and am indebted to I. J. D'Haenens and C. K. Asawa for technical assistance in obtaining the measurements. 中文

(187, 493-494; 1960)

T. H. Maiman: Hughes Research Laboratories, A Division of Hughes Aircraft Co., Malibu, California.

References:

1. Schawlow, A. L., and Townes, C. H., *Phys. Rev.*, **112**, 1940 (1958).
2. Javan, A., *Phys. Rev. Letters*, **3**, 87 (1959).
3. Sanders, J. H., *Phys. Rev. Letters*, **3**, 86 (1959).
4. Maiman, T. H., *Phys. Rev. Letters*, **4**, 564 (1960).

红宝石中的受激光辐射

梅曼

在20世纪初，阿尔伯特·爱因斯坦指出存在受激辐射跃迁现象，即一种特定频率的辐射是怎样从受激发介质中激发出更多同样频率的辐射的。这篇文章中，加利福尼亚州休斯研究实验室的西奥多·梅曼利用一块红宝石首次观察到了这种现象。这块红宝石的两端镀着反射型银膜，因此而形成的镜子构成了一个“光学谐振腔”，在这个“光学谐振腔”中光束反复地将处于激发态的镉离子激发并辐射出来。“受激辐射的光放大”是关于激光原理的第一次基本说明。 [英文](#)

肖洛和汤斯^[1]提出了一种以碱金属蒸气作为工作介质产生单色性极高的红外光辐射的技术。贾范^[2]和桑德斯^[3]也讨论了在电子激发气体中产生这种辐射的若干方案。在本实验室中，我们已经成功地将光泵浦技术用于固体荧光材料中，并以此获得了负温度及波长为6,943埃的受激光辐射，其中所用的工作介质是红宝石（含铬的刚玉）。 [英文](#)

图1给出的是该晶体中三价铬离子的能级结构简图。当我们用波长约为5,500埃的能量照射此材料时，铬离子被激发到 $4F_2$ 态，然后通过非辐射跃迁迅速损失部分激发能而跃迁到 $2E$ 态^[4]。随后这个能态通过自发辐射而缓慢衰变，辐射产生了明锐的双线，它们在温度为300 K时的波长分别是6,943埃和6,929埃（图2a所示）。在高强度的激发条件下，处于亚稳态（ $2E$ ）的粒子数将多于处于基态的粒子数，这就是产生负温度的条件，并最终导致受激辐射的光放大。 [英文](#)

Time's Arrow and Entropy

K. Popper

Physicists since the late nineteenth century had speculated over the links between time, thermodynamics and entropy. A related question, discussed by Erwin Schrödinger, is how life on Earth seems to produce ever-increasing complexity, and therefore lower entropy. Here the philosopher Karl Popper suggests that the mystery of increasing biological order may actually have more to do with the cooling of the planet than with its perpetual warming by the Sun. Popper argues that there does not appear to be any special link between the second law of thermodynamics and either the nature of time or biological processes on Earth. Physicist Ilya Prigogine, mentioned here, went on to propose a non-thermodynamic, quantum origin for the “arrow of time”. [中文](#)

SEVERAL years ago¹ I suggested that we should distinguish between two essentially different ways in which energy can be degraded or dissipated: “Dissipation in the form of increasing disorder (entropy increase) is one of them, and dissipation by expansion without increase of disorder is the other. For an increase of disorder, walls of some kind are essential: a sufficiently thin gas expanding in a ‘vessel without walls’ (that is, the universe) does not increase its disorder.” Reasons for this view were given in the place cited. [中文](#)

In order to explain this a little more precisely, I shall here introduce, following Prigogine², the term “system” to denote the (energy and

material) “contents of a well-defined geometrical volume of macroscopic dimensions” (so that, for example, an organism enclosed by its skin, or our solar system as enclosed by a sphere round the Sun with a radius of 10^5 light seconds, would be a “system”); and I shall speak of the “exterior” of a system X as a region of space (leaving it open whether or not this is in its turn a geometrically well-defined “system”) of which X forms a part. 中文

Following Prigogine, I shall distinguish between (materially or at least energetically) “open” and “closed” systems. (An energetically closed system is called “isolated”.) Moreover, I shall call a system X “essentially open” if it is part of a system Y such that all geometrically convex systems of which Y is a part are (at least energetically) open. (This definition makes it possible even for an isolated system to be essentially open.) 中文

I further call X “essentially open towards a cooler exterior” if X is enclosed by some convex system Y such that: (a) all elements of any sequence Z_i of convex systems of which Y is a part are essentially open and of a lower average temperature than Y , and that (b) for every such system Z_i there is a system Z_j which encloses Z_i and which is not of a higher average temperature than Z_i . 中文

The terminology here introduced makes it possible to clarify a number of points in connexion with the second law of thermodynamics which seem in urgent need of clarification. 中文

Again following Prigogine³, we can split the change of entropy dS_X in any system X into two parts: dS_{Xe} , or the flow of entropy due to interaction with the exterior of X , and dS_{Xi} , the contribution to the change of entropy due to changes inside the system X . We have, of course:

$$dS_X = dS_{Xe} + dS_{Xi}$$

(1)

and we can express the second law by:

$$dS_{Xi} \geq 0$$

(2)

中文

For an energetically closed (or “isolated”) system X , for which by definition $dS_{Xe} = 0$, expression (2) formulates the classical statement that entropy never decreases. But if X is open towards a cooler exterior:

$$dS_{Xe} < 0$$

(3)

holds, and the question whether its total entropy increases or decreases depends, of course, on both its entropy production dS_{Xi} and its entropy loss dS_{Xe} . 中文

The fact that entropy can decrease in an open system X does not, of course, conflict with the second law as given by expression (2). But the second law is often formulated in a different way; for example, it is said that “if we ... expand our system to include all the energy exchange, it would be found that in the larger system the entropy had increased. For example, to measure the entropy change taking place in living organisms as a whole, it would be necessary to include in our system the Sun and some additional portion of the universe, as well as the Earth itself”⁴. Thus it is suggested that for sufficiently large systems X of our universe, $dS_X \geq 0$, so that the entropy always increases. 中文

Yet, so far as our knowledge of the Universe goes, the precise opposite

appears to be the case. With very few and short-lived exceptions, the entropy in almost all known regions (of sufficient size) of our universe either remains constant or decreases, although energy is dissipated (by escaping from the system in question). This is so, at any rate, if we assume that the law of conservation of energy is valid; and it is also so if we assume the “steady state” theory of the expanding universe. (It is not so on the assumption of a finite and non-expanding universe with non-zero energy density.) [中文](#)

In order to see this, all that is needed is to be clear about the empirical fact that in our universe we know only essentially open systems, and only systems *X* which, so far as they produce entropy at all, are essentially open towards a cooler exterior. (This is true even of all so-called “closed” or “isolated” systems.) But for all such systems, one of the following cases must hold: (a) they are (practically) stationary, like the solar system and most stars known to us, in which case their entropy production (practically) equals their entropy loss, at least temporarily; or (b) they are losing temperature, and thereby entropy; or (c) they are producing more entropy than they lose, in which case they are in process of getting hotter, a process which, whether energy conservation is assumed or the steady state theory, can be only a comparatively rare and short-lived temporary process. (Even if the system in question should be one that collects matter from its environment until its gravitational field becomes so strong as to encapsulate and separate off the system from the rest of the universe, it would thereby presumably become stationary.) All we know about the universe points to (a) and (b) as being by far the most frequent and important cases: in almost all sufficiently large systems known to us, entropy production seems to be equalled, or even exceeded, by entropy loss through heat radiation. [中文](#)

This may be explained by the conjecture that every entropy-producing region is open towards some large (perhaps infinite) sinks of energy—

regions the energy capacity or heat capacity of which, at least for heat in the form of radiation, is infinite (or approximately so for all practical purposes). The existence of such sinks seems to be strongly indicated by the darkness of the night sky. (We might represent this conjecture by the model of an infinite universe with zero energy density; or by that of an energy-conserving expanding—and therefore cooling and entropy-destroying—universe which tends towards zero energy density; or by that of an expanding steady-state universe with constant temperature, and entropy production equalled by entropy escape.) 中文

So there do not seem to be theoretical or empirical reasons to attribute to expression (2) any cosmic significance or to connect “time’s arrow” with that expression; especially since the equality sign in expression (2) may hold, for almost all cosmical regions (and especially for regions empty of matter). Moreover, we have good reason to interpret expression (2) as a statistical law; while the “arrow” of time, or the “flow” of time, does not seem to be of a stochastic character: nothing suggests that it is subject to statistical fluctuation, or connected with a law of large numbers. 中文

As for the evolution of life, this seems to be connected, if at all, with a cooling rather than a heating process on Earth (or perhaps with periodic temperature fluctuations); that is, with increasing order and decreasing entropy. Yet it does not seem that “feeding on neg-entropy” has much to do with the preservation of life, as has been suggested, for example, by Schroedinger⁵. For during the incubation of birds’ eggs entropy rather than neg-entropy is supplied to them, though they are in a period of increasing organization; and while in an organism dying of heat or of fever entropy may increase, if it dies of cold—say, by deep-freezing—its entropy certainly decreases. 中文

Karl Popper: University of London.

References:

1. Popper, K. R., *Nature*, **178**, 381 (1956); **177**, 538 (1956); **179**, 1296 (1957); **181**, 402 (1958); *Brit. J. Phil. Sci.*, **8**, 151 (1957).
2. Prigogine, I., *Introduction to Thermodynamics of Irreversible Processes*, 3 (1955).
3. Prigogine, I., *Introduction to Thermodynamics of Irreversible Processes*, 16 (1955).
4. Blum, Harold F., *Time's Arrow and Evolution*, 15 (1935). (Similar statements are to be found, for example, on pages 16, 24, 33, 201.) Compare also Planck, M., *A Survey of Physics*, **17**, 27 (1925).
5. Schroedinger, E., *What is Life?* 72 (1944).

时间之箭和熵

波普尔

从19世纪末期起，物理学家们便开始思索时间、热力学和熵之间的相互联系。埃尔温·薛定谔曾讨论过一个与此相关的问题，即地球上的生命是如何不断地增加其复杂性，从而使熵值降低的。本文中，哲学家卡尔·波普尔认为生物有序性逐渐增加的奥秘实际上更多地在于地球自身的冷却，而不是由于太阳给地球的持续加温。波普尔认为热力学第二定律无论是与时间的本质还是与地球上的生物过程似乎都不存在任何特别的联系。本文还提到了物理学家伊利亚·普里高津进一步提出的“时间之箭”的非热力学的量子起源。 [英文](#)

几年前^[1]我曾指出，我们应该区分两种完全不同的使能量降低或耗散的途径：“一种是以增加无序性（熵增加）的形式进行耗散，另一种是不增加无序性，通过膨胀产生的耗散。某种形式的壁的存在对于无序性的增加是必不可少的：足够稀薄的气体在一个‘没有器壁的容器’（即宇宙）中进行膨胀并不会增加其无序性。”在前述引文中已给出了此观点的理由。 [英文](#)

为了对此进行更为精确的解释，在本文中我将引入普里高津^[2]定义的术语“系统”来表示“在宏观维度内给定几何体积之中的内含物”（能量和物质）（因此，如皮肤包被的有机体，或环绕太阳的半径为 10^5 光秒的球面之内的太阳系都属于此“系统”）；我将系统X的“外界”说成是一个空间区域（让它开放，无论这样反过来会不会是一个具有明确几何意义的系统），系统X形成了其中的一部分。 [英文](#)

按照普里高津的观点，我将（从物质或至少从能量的角度）区分“开放”系统和“封闭”系统。（所谓的“孤立系统”就是指一个能量封闭的系统。）此外，如果系统X是系统Y的一部分，我就称系统X是“基本开放

的”，这样包含系统Y的所有在几何上凸出的系统（至少在能量上）是开放的。（这个定义甚至使得一个孤立系统有可能是基本开放的。）

英文

另外，如果系统X被某些凸出系统Y所包围并满足以下条件：（a）包含Y的凸出系统的任意序列 Z_i 的所有元素都是基本开放的，并且它们的平均温度比系统Y的要低；（b）对于每一个这样的系统 Z_i ，都有一个包含 Z_i 在内的且温度不比 Z_i 高的系统 Z_j 存在，那么我称系统X“对更冷的外界基本开放”。

英文

本文中引入的术语有可能阐明与热力学第二定律有关的许多观点，该定律似乎亟待阐明。

英文

再次按照普里高津的观点^[3]，我们可将任何系统X熵值的变化 dS_X 分成两部分：由于与系统X的外界相互作用引起的熵的流动 dS_{Xe} ，以及由于系统X内部的变化引起的熵的变化 dS_{Xi} 。由此，我们可得：

$$dS_X = dS_{Xe} + dS_{Xi} \quad (1)$$

我们可用下式表示第二定律：

$$dS_{Xi} \geq 0 \quad (2)$$

英文

对于能量封闭的（或“孤立的”）系统X，我们通过定义可知 $dS_{Xe} = 0$ ，式（2）变成了经典表述：熵永不减少。但是，如果系统X对更冷的外界开放，则有：

$$dS_{Xe} < 0 \quad (3)$$

那么总熵是增加还是减少便自然取决于增加的熵 dS_{Xi} 和减少的熵 dS_{Xe} 分

别有多少。 英文

事实上，开放系统X中熵的减少与式（2）所表述的第二定律并不相矛盾，但第二定律通常用另一种方式来表述。例如，它可表述为“如果我们.....扩展我们的系统至其包含所有的能量交换，就会发现在更大的系统中熵增加了。又如，要测量整个生命有机体发生的熵变化时，在这个系统中有必要包含太阳以及宇宙某些其他的部分，还有地球自身”[4]。因此，如果X是宇宙中足够大的系统，则 $dS_X \geq 0$ ，那么熵总是增加的。

英文

然而，就我们对宇宙的认知不断地变化而言，完全相反的情况似乎也存在。除了极少的短暂的例外，宇宙中几乎所有已知（足够大的）地区的熵都是保持不变或减少的，虽然能量（从当前系统中逃逸出）耗散了。如果我们假设能量守恒定律成立，那么无论怎样都会有上述结论；如果我们假设膨胀宇宙的“稳态”理论也成立，那么上述结论仍然成立。（但是如果假设具有非零能量密度的宇宙是有限的和非膨胀的，那上述结论则不成立。） 英文

为了证明这一点，需要弄清这样一个经验事实，即在宇宙的宇宙中，我们只知道基本开放的系统，只知道系统X（只要它们还能产生熵）对更冷的外界基本开放。（即使对于所谓的“封闭的”或“孤立的”系统也是成立的。）但对上述所有的系统，下列情况之一必须成立：
（a）它们（实际上）是定态的，像太阳系和大多数我们已知的恒星，在这种情况下，至少暂时它们的熵产生（实际上）等于其熵减少；或者
（b）它们的温度正在降低，因此熵在减少；或者（c）它们正在增加的熵大于其减少的熵，在这种情况下，它们处于变热的过程中，无论我们假定能量是守恒的抑或是稳态理论，这个过程只能是一个比较罕见和短暂的瞬间过程。（尽管讨论的系统应该从外界环境中收集物质直到引力场增强到可以容纳这些物质并将系统和外部的宇宙分割开来，但是仍然可以假定这个系统是定态的。）我们对宇宙的所知显示出（a）和（b）是迄今为止最常见和最重要的两种情况：在几乎所有足够大的已知系统中，通过热辐射减少的熵可以抵消甚至超过产生的熵。 英文

这可以用下述推测来解释，即每一个正在产生熵的区域都是在向某

些大的（也许是无限大的）能量库开放的——它们的能量容量或热容量（至少对辐射形式的热容量）是无限的（或实际上就是近似于无限）。夜晚天空的黑暗似乎强有力地表明这些能量库的存在。（我们可以用能量密度为零的无限宇宙模型来表达这种推测；或用能量守恒的膨胀宇宙模型——其温度和熵都在减少——即用一种能量密度趋于零的宇宙模型表达这种推测；抑或用具有恒定温度的、熵的产生与熵的逃逸相等的膨胀稳态宇宙模型来表达这种推测。） [英文](#)

因此本文似乎并没有理论依据或经验依据赋予式（2）任何宇宙的意义，或把“时间之箭”同其联系起来；尤其因为式（2）的等号对几乎所有的宇宙区域（特别是对没有物质的真空）都能成立。此外，我们有很好的理由可以将式（2）解释为一种统计学定律；而时间之“箭”或者时间之“流”似乎并不具有随机的特性：没有证据说明它受统计性涨落支配或和大数定律相关。 [英文](#)

至于生物进化，似乎是（如果有的话）与地球上的冷却过程而不是与升温过程有联系（或者可能同周期性的温度涨落相联系）；也就是说，其与有序性增加和熵减少的过程有联系。然而，薛定谔^[5]提出似乎没有显示生命的维系与“摄入负熵”有很多联系。在鸟蛋孵化期间，尽管它们处于有机体增加的时期，但它们摄入的是正熵而不是负熵；在死于发热或高烧的有机体中熵可能增加，如果死于寒冷——比如深度冷冻——它们的熵肯定要减少。 [英文](#)

（沈乃徵 翻译；张元仲 审稿）

Opening Electrical Contact: Boiling Metal or High-density Plasma?

F. Llewellyn Jones and M. J. Price

The opening of an electrical contact may not appear to hide rich physics. Yet physicist Frank Llewellyn Jones and colleagues here report that the problem is more complex than usually thought. As a closed contact begins to open, the current flowing through it must follow an ever more constricted path. This will necessarily cause great heating, and perhaps even boiling of the metal. Indeed, their simple calculations suggest that small volumes of metal of the order of 10^{-12} cm³ should be lost upon each opening, eventually damaging the contact. The researchers also show a series of high-speed photographs documenting the formation of tiny bridges of metal between contacts, which are key to understanding the process. [中文](#)

THE processes occurring at the opening of a low-voltage (~ 4 V) electrical contact have considerable fundamental physical interest as well as having practical importance in the field of electronic and communication engineering. It is well known¹ that, starting with the electrodes closely pressed together in the fully closed position, the opening process leads to a constriction of the current stream lines, which can produce intense local heating and melting of the

penultimate microscopic region of contact. The maximum temperature in the contact is related to the potential difference by the ψ , θ theorem:

$$\psi = \left[2 \int_{\theta}^{\theta_m} \frac{\lambda}{\kappa} d\theta \right]^{1/2} \quad (1)$$

where ψ = a generalized potential equal to the electrical potential in the absence of thermo-electric effects, θ = temperature, λ = thermal conductivity and κ = electrical conductivity. Thus, on gradual separation of the electrodes the constriction resistance increases and the temperature rises up to and past the melting-point of the metal. On continuing the withdrawal the molten volume thus increases and gets drawn out into a microscopic bridge of molten metal joining the solid electrodes; the contacts finally separate and the circuit opens only when this bridge is broken. The rupture process, however, can be very complicated and lead to transfer of metal from one electrode to the other, a process which, when continually repeated, can lead to the “pip” and “crater” formation which renders the contacts useless after some time. There is evidence^{1,2} to show that the matter transferred per operation ($\sim 10^{-12}$ cm³ in a 5-amp circuit) is related to the size of the molten metal bridge (width $\sim 10^{-4}$ cm/amp), so that the stability, growth and final rupture of the bridge are a matter of importance, not only from practical considerations, but also from the point of view of the physical properties of metals in the molten state and at high temperatures. [中文](#)

In the first place, an important condition of equilibrium, at least in the earlier stages, is that which depends on the application of surface tension forces. The shapes of the bridges would then be surfaces of revolution satisfying the equation:

$$\Delta p = T \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \quad (2)$$

and these are unduloids, catenoids or nodoids according as Δp is positive, zero or negative respectively³. Photographs of static microscopic bridges have indeed confirmed that these stable shapes can be attained¹. In the later stages of opening Δp will be negative, and experiment has established that the final stable shape is usually the nodoid. The ψ , θ theorem shows that the hottest region of the microscopic molten metal bridge between like electrodes will probably be the narrow neck and, at first sight, it might appear that this is the region at which the bridge is most likely to break. However, detailed investigation of this final process raises some important problems in the physics of metals at high temperatures, and, in particular, near their boiling points. [中文](#)

Mechanisms of Break

It can be seen at once from the ψ , θ theorem that the mechanism of rupture of the molten metal bridge involves the physical properties of the metal, not at any one temperature, but over a wide range of temperatures up to boiling-point, and a number of different processes of rupture are possible. [中文](#)

In the first place, continued separation of the electrodes and the drawing out of the bridge increases the contact resistance R_c ; consequently, the contact voltage $V_c (= R_c I_c)$ for a given circuit current I_c continually rises. Inspection of the ψ , θ theorem shows that the maximum temperature θ_m correspondingly increases; in fact, it is readily seen by using the Wiedermann-Franz law that, when V_c exceeds about 1.5 V, the corresponding value of θ_m from (1) exceeds the boiling-point of any known metal. Thus, this process of rise of maximum temperature may well continue until θ_m reaches the boiling-point θ_b so breaking the molten metal bridge. The voltage V_b at which this occurs is called the boiling voltage, and is related to θ_b by equation (1). Further analysis⁴ of the ψ , θ theorem shows that, since the relationship between ψ and θ depends on the variation of λ/K

with θ , thermal instability can occur for certain functional relationships of λ/κ with θ , in which case a sudden rise of θ_m up to the boiling point can, in certain circumstances, take place. Measurements of the contact current, potential difference and maximum temperature, and its location, enable a determination to be made of the transport properties of metals such as their thermal and electrical conductivities and Thomson coefficients and their dependence on temperature to be determined for the molten state at high temperatures¹. [中文](#)

These thermal effects, however, are not the only processes which may sever the bridge. For example, the electromagnetic pinch effect might well, with large currents, so constrict the bridge at the narrowest, hottest and therefore weakest point as to rupture it there. Again, the known variation of surface tension with temperature is an important factor influencing the stability of the bridge, and the consequences of this can only be neutralized by the influence of surface impurities or compensating internal viscous motions in the bridge. Restriction due to the size and geometry of the actual electrodes in a given practical contact might well prevent the continued formation of the stable nodoid form, and instability could result. [中文](#)

The shape and volume of the final bridge and its mechanism of rupture are very important from the practical point of view on account of their relation to the rate of matter transfer on rupture. For example, suppose that a thermo-electric effect displaced the hottest section of the molten metal bridge towards one electrode, then it follows that the rupture at that particular section could have the effect of producing net transfer from one electrode to the other. The amount transferred may then only be that of the hottest region in the neck. On the other hand, if, in a different process of rupture, the molten metal bridge disintegrated as a whole and was transferred to one or other electrode (say, by mechanical splashing of minute droplets), then in

this case the matter transfer could be relatively high and this, of course, could have serious practical effects. [中文](#)

Thus, the precise processes of the actual opening of the circuit are a matter of considerable practical and theoretical importance, and these phenomena have been under investigation at Swansea for some time. The relationships of the size of the molten metal bridge to the current and to the matter transferred per operation and the local self-inductance have been investigated^{1,5-10}. [中文](#)

Accurate measurement of the amount of metal of a given electrode ($\sim 10^{-12}$ g) actually transferred on the rupture of the molten metal bridge was found possible using the radioactive tracer technique, and a very rapid variation with local inductance, particularly in the range 10^{-6} to 10^{-8} H, was found for a number of metals and, particularly so, for platinum^{1,6-9}. Further, optical examination of the crater formed on bridge rupture indicated that in some metals the whole volume of the molten metal bridge took part in the transfer. The shape and volume of the microscopic bridge were determined from the geometry of the melting isothermals in each electrode after rupture. [中文](#)

Facts such as these are difficult to reconcile with the picture of matter transfer occurring as the result of a mechanical splashing of small droplets formed from the disintegrating molten metal bridge. On the contrary, they are more consistent with the view that the transfer may well be ionic, the motions of the ions being determined by the oscillatory electric field between the electrodes after the bridge has broken. For reasons such as these an alternative view was put forward based on the production of a micro-plasma, possibly initially formed at the broken neck of the molten metal bridge¹¹. Consequently, in recent years effort has been directed to finding direct evidence for the existence of such a plasma. It will be appreciated that, owing to the speed of events in the final stages of the development of the molten metal bridge, extensive expansion of the plasma to a size which can

readily be seen may not take place. In fact, particularly in the presence of a high-pressure ambient atmosphere, a plasma of metal vapour might well be severely restricted in size throughout its short life. [中文](#)

Photography of the Microscopic Molten Metal Bridge

Early attempts to photograph the development of the exploding bridge were confined to cases in which it would be expected that surface tension would be the dominant controlling force and large stable bridges obtainable. Such photographs have been previously obtained for large iron bridges in air¹. In appropriate circumstances the oxide film on the surface would enable a constant surface tension to be set up over the whole surface, and thus produce stability in accordance with (2). [中文](#)

A number of standard ciné films (25 f.p.s.) were taken of the formation, development and final rupture of the bridge, and many thousands of frames were examined in the hope of finding an illustration of the actual rupture. One or two frames were found which showed that the actual rupture process might not be a simple parting of the nodoid, and this indicated that it was necessary to use high-speed photography if rupture was to be examined in more detail. There were considerable difficulties in the high-speed photography of the molten bridge mainly on account of the small area to be photographed ($\leq 10^{-4}$ cm²), the low luminosity for metals other than platinum and tungsten, and the difficulty associated with the synchronization of the camera and the phenomenon to be photographed. A certain degree of elusiveness of the bridge at all stages of its life also made photography difficult. However, an optical system incorporating a high-speed camera was designed and constructed to examine the development of a molten metal bridge for time-intervals down to about 10 μ sec. In this way a large number of metals were investigated under varying conditions of ambient

atmosphere and pressure. Some preliminary photographs thus obtained were shown at conferences at Oklahoma⁵, at Graz⁹ and at Berlin¹⁰. Sets of later photographs giving a succession of frames extending over a total time of a few milliseconds covering in some detail various phases of the rupture of the microscopic molten metal bridge are given here. The results for iron are of particular interest in that they illustrate the three different aspects of the rupture process discussed here, and these are given in Figs. 1, 2 and 3. [中文](#)

Fig. 1 shows a series of photographs at a rate of 10^4 frames per sec and deals with iron in air. Doubtless on account of consequent oxidation affecting the surface tension, well-shaped stable bridges were formed after a number of operations, and these are in accordance with the theoretical prediction of the stable nodoid. Stability could be controlled by surface tension forces, and the fact that the bridge ruptured when the hottest section boiled is clearly indicated by the photographs, which show the two white-hot separate parts of the bridge after rupture. [中文](#)



Fig. 1



Fig. 2



Fig. 3

Fig. 1. Material, iron; atmosphere, air; current, 30 amp; circuit E.M.F., 6 V; polarity, top electrode negative; magnification, $\times 6$; framing rate, 5,000 f.p.s.

Fig. 2. Material, iron; atmosphere, air; current, 30 amp; circuit E.M.F., 6 V; polarity, top electrode negative; magnification, $\times 6$; framing rate, 2,000 f.p.s.

Fig. 3. Material, iron; atmosphere, vacuum; current, 60 amp; circuit E.M.F., 6 V; polarity, top electrode positive; magnification, $\times 19.5$; framing rate, 7,000 f.p.s. 中文

Fig. 2 illustrates a less stable condition in which the degree of oxidation was such that the surface tension could not be maintained constant over the surface. In such cases stability can only be produced by internal viscous motion, and this is consistent with the effect illustrated by the rapid change from frame to frame in the location of the hottest region of the bridge surface. 中文

In order to minimize the effect of surface tension forces in establishing stability, the iron surfaces were cleaned by a glow-discharge treatment in hydrogen and the contact was also operated in a vacuum in order to avoid further oxidation. The development of the bridge in this case is illustrated by the series in Fig. 3. This is dramatically different from the two series in Figs. 1 and 2 in that the molten metal bridge no

longer severs over a very small section while the bridge remains in the liquid form. On the contrary, in this case an electric micro-discharge appears to have been formed from the completely exploded bridge, producing a high-density plasma of great brightness the duration of which is less than 100 μsec and probably less than 10 μsec . On account of the inability to expand appreciably in these conditions, the particle density in the micro-plasma must be extremely high. 中文

Similar effects have been found for other metals, and the radio-tracer technique enables the directions of the metallic transfer occurring during this short existence of the plasma to be measured. 中文

We thank Mr. Ieuan Maddock of the Atomic Weapons Research Establishment, U.K. Atomic Energy Authority, Aldermaston, for the loan of a high-speed camera and for advice. One of us (M. J. P.) is also grateful for the award of a Department of Scientific and Industrial Research postgraduate research studentship. Thanks are also due to the Royal Society for a grant for the purchase of precious metals.

中文

(207, 255-257; 1965)

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References:

1. Llewellyn Jones, F., *Physics of Electrical Contacts* (Clarendon Press, 1957).
2. Llewellyn Jones, F., *Proc. Intern. Res. Symp. Electric Contact Phenomena*, University of Maine (1961).
3. Davidson, P. M., *Brit. J. App. Phys.*, **5**, 189 (1954).
4. Greenwood, J. A., and Williamson, J. B. P., *Proc. Roy. Soc., A*, **240**, 13 (1958).
5. Llewellyn Jones, F., *Proc. Twelfth Intern. Conf. Electromagnetic Relays*, Oklahoma State Univ. (1964).
6. Price, M. J., *Proc. Thirteenth Intern. Conf. Electromagnetic Relays*, Oklahoma State Univ. (1965).
7. Jones, C. R., Hopkins, M. R., and Llewellyn Jones, F., *Brit. J. App. Phys.*, **12**, 485 (1961).
8. Jones, C. H., and Hopkins, M. R., *Brit. J. App. Phys.*, **14**, 137 (1963).
9. Llewellyn Jones, F., *Proc. Intern. Symp. Electrical Contacts*, Technische Hochschule, Graz,

Austria (1964).

10. Hopkins, M. R., *Proc. Intern. Symp. Electrical Contacts*, Technische Hochschule, Graz, Austria (1964).
11. Llewellyn Jones, F., *Proc. Third Intern. Conf. Ionization Phenomena in Gases*, Venice, **2**, 620 (1958).
12. Llewellyn Jones, F., *Proc. Intern. Conf. Electrical Contacts*, Deutsche Akademie der Wissenschaften zu Berlin (1964); also *Elektrie*, **3**, 129 (1965).

断电接触：沸腾的金属还是高密度等离子体？

卢埃林-琼斯，普赖斯

电接触的断开中似乎不会藏有高深的物理意义。然而，在本文中物理学家弗兰克·卢埃林 - 琼斯及其同事们指出：这个问题比人们通常想象的要复杂得多。在一个闭合电路的接触即将断开的时候，通过它的电流一定会经过一个更加狭窄的路径。这种情况必然会产生大量的热，甚至导致金属的沸腾。确实，他们通过简单的计算表明在每次断开电路时都会有体积为 10^{-12} 厘米³数量级的小块金属消失，最终使这个电接触毁坏。研究者们也展示了一系列电接触间形成的微小金属桥的高速照相图片，这是理解此过程的关键。 [英文](#)

低压下（约为4伏特）电接触断开的过程有重要的基础物理学意义，同时对电子工程学和通信工程领域也有重要的实用价值。众所周知^[1]，初始状态是两个电极紧压在一起处于完全导通的状态，断开过程中会导致电流线的收缩，这会导致在最后的微观接触区域产生很强的局部加热和熔化。在接触区的最高温度与电势差有关，可以通过 ψ ， θ 定理表示，如下式：

$$\psi = \left[2 \int_0^{\theta_m} \frac{\lambda}{\kappa} d\theta \right]^{1/2} \quad (1)$$

式中 ψ 为广义势（在没有热电效应情况下就等于电势）， θ 为温度， λ 为热导率， κ 为电导率。因此，随着电极的逐渐分离，收缩电阻增大，温度升高并超过了金属的熔点。继续分离，熔化的体积随之增加，这种熔融金属逐渐被拉成连接着两个固体电极的微观桥；电接触最终会断开，但只有这个微观的桥断开时整个电路才会断开。然而，这个断裂过程可

能是非常复杂的并且会导致金属从一个电极转移到另一个电极上，当不断重复这个过程时，便会产生“点”和“坑”状形态，以致过一段时间后触点失效。有证据^[1,2]表明，每次操作过程中物质的转移量（在电流为5安培的电路中约10-12厘米³）与熔融金属桥的尺寸（宽度约为10-4厘米/安培）有关，因此桥的稳定性、增长性以及最终的断裂都是具有重要意义的，这不仅是对实际应用而言，而且对研究熔融状态和高温状态下金属的一些物理性质也有重要意义。 [英文](#)

首先，至少是在较早期阶段，达到平衡的一个重要条件取决于表面张力的应用。桥的形状将由满足式（2）的旋转曲面构成：

$$\Delta p = T \left(\frac{1}{R_1} + \frac{1}{R_2} \right) \quad (2)$$

当 Δp 分别为正值、零或负值^[3]时，形态依次是类波状、类链状或类结节状。静态微观桥的照片的确已证实这些稳定形态是可以达到的^[1]。在断开的较后期阶段， Δp 将是负值，实验已证实最终的稳定形态通常是类结节状。 ψ, θ 定理表明，相同电极间的微观熔融金属桥中最热的区域可能位于窄口处，初看之下，这里非常有可能就是金属桥即将断裂的地方。然而，有关这个最终过程的详细研究引发出了一系列高温下金属物理的重要问题，尤其在接近沸点时。 [英文](#)

断裂的机制

从 ψ, θ 定理可以一目了然地看出，熔融金属桥的断裂机制涉及许多金属的物理性质，但断裂并不是发生在某一特定温度下，而是在逼近沸点的较大温度范围内都会发生，许多不同的断裂过程都是有可能的。

[英文](#)

首先，电极的连续分离和桥的拉长增大了接触电阻 R_c ；结果，对于给定的回路电流 I_c ，其接触电压 $V_c (= R_c I_c)$ 连续增高。对 ψ, θ 定理的分析表明，最高温度 θ_m 相应地增高；实际上，用威德曼 - 弗朗兹定律很容易看出，当接触电压 V_c 超过约1.5伏特时，由式（1）得出的 θ_m 对应值超出了任何已知金属的沸点。因此使最高温度上升的过程会持续下去直至 θ_m 达到沸点 θ_b ，从而使熔融金属桥断裂。此时的电压 V_b 称为沸点电压，

它通过式(1)与 θ_b 相关。对 ψ , θ 定理做进一步分析^[4]可知, 由于 ψ 和 θ 的关系取决于 λ/κ 随 θ 的变化, 因此 λ/κ 和 θ 之间具有特定的函数关系时可以产生热的不稳定性, 在这种情况下, θ_m 在特定的环境中可能突然上升至沸点。通过测量接触电流、电势差和最高温度及其位置, 便能得出金属的输运性质, 例如, 金属的热导率、电导率和汤姆孙系数以及这些性质在高温熔融态下与温度之间的关系^[1]。 [英文](#)

然而, 这些热效应并不是导致桥断裂的唯一过程。例如, 电磁箍缩效应可产生很大的电流, 因此在最窄、最热因而最薄弱的点使桥收缩, 并导致其断裂。此外, 已知的表面张力随温度而变化也是影响桥稳定性的一个重要因素, 这些结果只能被表面杂质的影响或对桥内部黏滞运动的补偿所抵消。在特定的实际电接触中, 由于真实电极尺寸和几何形状的限制会有效地阻止稳定类结节状桥的连续形成, 从而使其具有了不稳定性。 [英文](#)

从实际的观点看, 考虑到最终桥的形态和尺寸及其断裂机制与桥断裂时物质转移的速率有关, 所以它们都是非常重要的。例如, 假定热效应会将熔融金属桥的最热部分移向某个电极, 则将引起在某个特定位置上发生断裂并导致从一个电极净转移到另一个电极的效果。那么传递的量只是颈部最热区域的量。另一方面, 在另一不同断裂过程中, 熔融金属桥作为整体分解, 并转移到一个或另一个电极(譬如说, 通过微滴的机械喷溅), 那么在这种情况下, 物质转移量可以相当高, 当然, 这也可能具有重大的实际影响。 [英文](#)

因此, 电路实际断开的详细过程是一个具有重要的应用性和理论性的课题, 我们在斯旺西大学已对此现象做了一段时间的研究。研究人员也对熔融金属桥的尺寸与电流、每次操作中转移动的物质以及局部自感之间的关系开展了研究^[1,5-10]。 [英文](#)

采用放射性示踪技术, 能够精确测量出在熔态金属桥断裂时实际转移到给定电极的金属量(约为 10^{-12} 克)。人们已发现在许多金属中, 特别是铂^[1,6-9]中, 局部电感(尤其是在 10^{-6} 亨~ 10^{-8} 亨之间)有很快的变化。并且, 通过对由桥断裂形成的坑状结构进行的光学检测发现, 在一些金属中, 整个熔融金属桥的体积都参与了转移。这个微观桥的形态和

大小取决于各个电极断裂后熔融等温线的几何形状。

英文

这些情况很难与由熔融金属桥分解时产生的微滴机械喷溅而导致的物质转移图像相吻合。相反，这些情况与如下观点更为一致，即这种物质的转移是呈离子态的，而这种离子的运动取决于熔融金属桥断裂后在电极间振荡的电场。由于上述原因，人们提出了另一种基于微等离子体产物的观点，这一微等离子体很有可能最初形成于熔融金属桥的断裂颈上^[11]。因此，近年来我们努力寻找这类等离子体存在的直接证据。可喜的是，由于熔融金属桥发展的最后一步的变化速度，使得等离子体扩张到能易于看到的尺寸的情况并没有发生。实际上，尤其是在高压环境的气氛下，在金属蒸气等离子体的短寿命内，它的大小受到了严格的限制。

英文

微观熔融金属桥的拍摄

早期对于拍摄桥断裂过程的尝试受到一些条件的限制，因为人们认为表面张力会成为首要的控制力，从而能获得大而稳定的桥。这样的照片最先是在空气^[1]中对大的铁金属桥拍摄而得。在适宜的环境下，表面上的氧化膜将在整个表面范围内产生恒定的表面张力，因此得到如式（2）中的稳定性。

英文

我们采用许多标准的电影胶卷（25帧/秒）对桥的形成、发展和最终的断裂过程进行拍摄，我们对成千上万个镜头进行分析，希望能够发现桥实际断裂时的景象，最终找到了一两个镜头，显示出实际的断裂过程可能不是一个简单的类结节体的分开，并且这也表明如果想对断裂进行更细致地分析，就必须使用高速照相机。利用高速照相机拍摄熔融金属桥面临相当多困难，这主要是因为拍摄的目标范围非常小（小于等于 10^{-4} 厘米²），除铂金属和钨金属外，其他金属的亮度都很低，控制好现象发生与拍摄的同步也很困难。此外桥在寿命中不同阶段持续的时间不好把握，这同样为拍摄带来了困难。尽管如此，还是设计和制造了一个结合了高速照相机的光学系统，它能够以约为10微秒的时间间隔对熔融金属桥的断裂过程进行拍摄。利用这种方法，我们在不同的气氛和气压下对大量的金属进行了研究。通过这种方式获得的一些初步的照片，在俄克拉荷马州^[5]、格拉茨^[9]和柏林^[10]的会议上进行了展示。这里给出

几组后来得到的照片，照片拍摄到一段连续的镜头，覆盖了几毫秒内微观熔融金属桥断裂时不同阶段的一些细节。铁金属的结果格外有趣，因为它们说明了本文中讨论的在不同条件下断裂过程的三种状态，结果如图1、图2和图3中所示。 [英文](#)

图1示出了以每秒 10^4 帧拍摄到的一系列照片，其中金属铁是在空气中处理的。毫无疑问的是随后的氧化反应会影响到表面张力，在经过多次操作后才最终形成形状完好的稳定桥，并且这与稳定的类结节型桥的理论预测是相一致的。稳定性受到表面张力的控制，事实上照片清楚显示出，桥是在最热部分沸腾时断裂的，并且在断裂后形成两个白热分离的部分。 [英文](#)



图 1



图 2



图 3

图1. 材料：铁；气氛：空气；电流：30安培；回路电动势：6伏特；极性：顶部电极为负极；放大倍数： $\times 6$ ；帧速率：5,000帧/秒。

图2. 材料：铁；气氛：空气；电流：30安培；回路电动势：6伏特；极性：顶部电极为负极；放大倍数： $\times 6$ ；帧速率：2,000帧/秒。

图3. 材料：铁；气氛：真空；电流：60安培；回路电动势：6伏特；极性：顶部电极为正极；放大倍数： $\times 19.5$ ；帧速率：7,000帧/秒。 [英文](#)

图2示出一个稍不稳定的条件，该条件下氧化的程度使表面张力不

能在表面保持不变。这种情况下，稳定性仅靠内部的黏滞运动产生，并且这与用桥表面最热区域处帧 - 帧之间的快速变化说明的效应是一致的。 [英文](#)

在稳定性的建立过程中为了使表面张力的效应最小，我们利用在氢中辉光放电处理法对铁的表面进行了清洗，而且为了避免进一步的氧化，接触在真空中进行。在这种情况下建立的桥通过图3中的系列照片进行了说明。这与图1和图2的两个系列照片有很大差别，图3中当熔融金属桥以液体的形式存在时，其不会以很小的截面分离。相反，在这种情况下，在完全分解的桥上已出现电的微放电，在小于100微秒或可能小于10微秒的时间内产生了高亮度的高密度等离子体。由于在这些情况下无法明显地扩展，因此微等离子体中的粒子密度必然是极高的。

[英文](#)

在其他金属中已发现了类似效应，放射性示踪技术使在存在等离子体的这段极短时间内对金属转移方向进行测定成为可能。 [英文](#)

我们感谢位于奥尔德马斯顿的英国原子能管理局原子武器研究中心的爱恩·马多克先生借给我们一台高速照相机并提供了一些建议；感谢科学及工业研究署颁发给我们之间的一员（普赖斯）的研究生研究奖学金，也同样感谢皇家学会同意为给我们购买一些贵金属。 [英文](#)

（沈乃澂 翻译；赵见高 审稿）

Structural Basis of Neutron and Proton Magic Numbers in Atomic Nuclei

L. Pauling

Physicists by the mid 1960s had noted the surprising stability of atomic nuclei having certain “magic numbers” of either protons or neutrons, including 2, 8, 20, 50, 82 and 126. Here American chemist Linus Pauling offers an explanation. These numbers do not correspond to atomic shells being completely filled with fermions (particles with spin $1/2$, like protons and neutrons). However, they do appear to correspond to closed shells of nucleons which achieve efficient packing in space, possibly with an extra halo of alpha particles. For example, the magic number 50 arises as 8 neutrons or protons in a closed-shell core, and another 42 in an outer halo. These magic-number nuclei have a higher average binding energy than other nuclei. [中文](#)

IN 1933 Elsasser¹ pointed out that some of the properties of atomic nuclei correspond to greater stability for certain numbers of neutrons and protons (given the name magic numbers) than for other numbers; the magic numbers for both N (neutron number) and Z (proton number) are 2, 8, 20, 50, 82 and 126. (Less-pronounced effects are observed also for N or Z equal to 6, 14, 28, 40, and some larger numbers. The set of magic numbers is often assumed to include 28.)

The magic numbers do not have the values $(2n^2)$ for completed shells of fermions (with all states with total quantum number n , azimuthal quantum number $l \leq n-1$, occupied by pairs), which are 2, 8, 18, 32, 50, ..., nor the values for certain shells and sub-shells that lead to maximum stability for electrons in atoms, which are 2, 10, 18, 36, 54 and 86. 中文

It was discovered by Mayer² and by Haxel, Jensen and Suess³ that the magic numbers can be accounted for by use of the sub-sub-shells corresponding to spin-orbit coupling of individual nucleons; that is, to the values of $j = l + 1/2$ and $l - 1/2$ for the two sub-sub-shells of each sub-shell. For example, they⁴ assign to N or $Z = 50$ the configuration

$(1s_{1/2})^2(1p_{3/2})^4(1p_{1/2})^2(1d_{5/2})^6(2s_{1/2})^2(1d_{3/2})^4(1f_{7/2})^8(2p_{3/2})^4(1f_{5/2})^6$ which may be written more briefly as $1s^2 1p^6 1d^{10} 2s^2 2p^6 1f^4 (1g_{9/2})^{10}$.

The evidence for spin-orbit coupling and for the Mayer–Jensen shell model is convincing. It is, however, difficult to understand, on the basis of their arguments, why the six magic numbers should be outstanding among the many numbers corresponding to the completion of spin-orbit sub-sub-shells, which (for the Mayer–Jensen sequence⁴ of energy-levels) are 2, 6, 8, 14, 16, 20, 28, 32, 38, 40, 50, 56, 64, 68, 70, 82, 92, 100, 106, 110, 112, 126, 136, 142, 中文

In the course of developing a theory of nuclear structure based on the assumption of closest packing of clusters of nucleons⁵, I have found that the magic numbers have a very simple structural significance: 2 and 8 correspond to the closed shells $1s^2$ and $1s^2 1p^6$, and the others to a closed-shell core with an outer layer (the mantle of the nucleus) containing the number of spherons (helions⁶, He^4 , tritons, H^3 , or dineutrons) required to surround the core in closest packing. 中文

Triangular (icosahedral) closest packing, as found, for example, in the intermetallic compound⁷ $\text{Mg}_{32}(\text{Al,Zn})_{49}$, involves the sequence 1, 12, 32, 72 of spheres in successive layers. These numbers are approximated by the equation $n_0 = (n_i^{1/3} + 1.30)^3 - n_i$, in which n_0 is the number of spheres in an outer layer and n_i is the number in the core. (The form of this equation corresponds to assigning equal effective volumes to the spheres, and the value of the constant reflects the nubbly surface and the packing of outer spheres into pockets of the core.) This equation can be applied to obtain the number of spherons in the successive layers in a nucleus, and thus to obtain the sequence of nucleonic energy-levels. Sub-shells (with given value of l) occurring once (as $1s$, $1p$, etc.) are assigned to the mantle of spherons, those occurring twice ($1s$ and $2s$, for example) to the mantle and next inner layer, and so on. Thus I interpret the configuration for N or $Z = 50$, given above, as representing 8 neutrons or protons in the core ($1s^2 1p^6$) and 42 in the outer layer ($2s^2 2p^6 1d^{10} 1f^{14} (1g_{9/2})^{10}$).

中文

The application of the packing equation leads to a sequence of levels essentially as given by Mayer and Jensen, but often with sub-sub-shells for different layers being filled over overlapping ranges of values of N or Z . For example, the $3s_{1/2}$, $2d_{3/2}$, and $1h_{11/2}$ sub-sub-shells all begin to be occupied at about N or $Z = 60$ and are all completed at about N or $Z = 82$. 中文

The configurations found in this way for the magic numbers are given in Table 1 and Fig. 1. Each of the first two represents a completed shell. The third (20) has a completed shell as core and another as mantle. Each of the others has a core of a completed shell or two completed shells, with a mantle that is required by the packing to include a sub-sub-shell $(1g_{9/2})^{10}$ for 50, $(1h_{11/2})^{12}$ for 82, and $(1i_{13/2})^{14}$ for 126. Until 184 is reached, there are no other values of N or Z for which the packing equation leads to a core consisting of

layers that are completed shells. 中文

Table 1. Nucleon configurations for magic numbers

<i>N</i> or <i>Z</i>	Mantle	Core or outer core	Inner core
2	$1s^2$		
8	$1s^2 1p^6$		
20	$2s^2 1p^6 1d^{10}$	$1s^2$	
50	$2s^2 2p^6 1d^{10} 1f^{14} (1g^9/2)^{10}$	$1s^2 1p^6$	
82	$3s^2 2p^6 2d^{10} 1f^{14} 1g^{18} (1h^{11}/2)^{12}$	$2s^2 1p^6 1d^{10}$	$1s^2$
126	$3s^2 3p^6 2d^{10} 2f^{14} 1g^{18} 1h^{22} (1i^{13}/2)^{14}$	$2s^2 2p^6 1d^{10} 1f^{14}$	$1s^2 1p^6$

中文

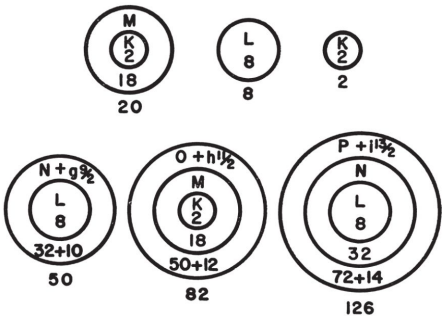


Fig. 1. The magic-number structures of atomic nuclei 中文

I conclude that the stability that characterizes the magic numbers results from the completion of shells for a single layer (2, 8) or two layers (20) of spherons, or, for the larger magic numbers (50, 82, 126), for the core layers, the mantle having a completed shell plus a completed sub-sub-shell. 中文

(208, 174; 1965)

L. Pauling: Big Sur, California.

References:

1. Elsasser, W. M., *J. Phys. et Radium*, **4**, 549 (1933); **5**, 389, 635 (1934).
2. Mayer, M. Goeppert, *Phys. Rev.*, **75**, 1969 (1949).
3. Haxel, O., Jensen, J. H. D., and Suess, H. E., *Phys. Rev.*, **75**, 1766 (1949); *Z. Physik*, **128**, 295 (1950).
4. Mayer, M. Goeppert, and Jensen, J. H. D., *Elementary Theory of Nuclear Shell Structure*, 58 (John Wiley and Sons, Inc., New York and London, 1955).
5. This theory is described in papers to be published in *Phys. Rev. Letters*, *Proc. U. S. Nat.*

Acad. Sci., and Science.

6. Pauling, L., *Nature*, **201**, 61 (1964); Proposal of the name helion for the α -particle.
7. Bergman, G., Waugh, J. L. T., and Pauling, L., *Nature*, **169**, 1057 (1952); *Acta Cryst.*, **10**, 254 (1957). Pauling, L., *The Nature of the Chemical Bond*, third ed., 427 (Cornell University Press, Ithaca, New York, 1960).

中子和质子在原子核中的幻数的结构基础

鲍林

在20世纪60年代中期，物理学家注意到，那些出奇稳定的原子核都含有一些特定“幻数”的质子或中子，这些“幻数”包括2、8、20、50、82和126。本文中，美国化学家莱纳斯·鲍林提出了一种解释：他认为这些幻数并不对应于那些完全被费米子（自旋为 $1/2$ 的粒子，例如质子和中子）填满的原子壳层。而是看起来对应于在空间中被有效堆积的核子的闭壳层，可能还带有一圈外加的 α 粒子晕。例如，幻数50就意味着在闭壳层核心内有8个中子或质子，另外42个在外层晕中。与其他原子核相比，这些幻数核具有更高的平均结合能。 [英文](#)

艾尔萨瑟^[1]于1933年指出，较之于其他数，具有某些特定中子数和质子数（将其命名为幻数）的原子核的一些性质更为稳定。对于 N （中子数）和 Z （质子数），这些幻数是2、8、20、50、82和126。（对于 N 或 Z 等于6、14、28、40以及某些更大的数，也能注意到不太明显的效应。通常认为幻数序列包括28。） [英文](#)

幻数既不是与费米子满壳层（或者说费米子成对填满主量子数为 n 、角量子数为 $l \leq n - 1$ 的所有状态）有关的数值（ $2n^2$ ），即2、8、18、32、50……也不是与某些可导致电子在原子中有最大稳定性的壳层和子壳层有关的数值：2、10、18、36、54和86。 [英文](#)

梅耶夫人^[2]以及哈克塞尔、延森和苏斯^[3]都发现，幻数可以利用对应于独立核子的自旋-轨道耦合的支壳层来进行解释；也就是说，对应于某一子壳层的总角动量分别为 $j = l + 1/2$ 和 $l - 1/2$ 的两个支壳层。例

如，他们^[4]将N或Z为50的组态标记为 $(1s1/2)^2 (1p3/2)^4 (1p1/2)^2 (1d5/2)^6 (2s1/2)^2 (1d3/2)^4 (1f7/2)^8 (2p3/2)^4 (1f5/2)^6 (2p1/2)^2 (1g9/2)^{10}$ ，或更简略地写成 $1s^2 1p^6 1d^{10} 2s^2 2p^6 1f^{14} (1g9/2)^{10}$ 。

英文

有关自旋-轨道耦合和梅耶夫人-延森壳层模型的证据是令人信服的。然而，对于他们的论据，让人难以理解的是，为什么这6个幻数在可以填满自旋-轨道耦合的支壳层的数字集合中是如此与众不同，这个集合（对于能级的梅耶夫人-延森序列^[4]）是2、6、8、14、16、20、28、32、38、40、50、56、64、68、70、82、92、100、106、110、112、126、136、142……

英文

在构建基于核子集团最密堆积假设的核结构理论^[5]的过程中，我已发现，幻数具有非常简单的结构意义：2和8对应于闭壳层组态 $1s^2$ 和 $1s^2 1p^6$ ，而其他的则对应于带有一个外层（称为核的幔壳层）的闭壳层核，其中外层内含有一定数量的球子（氦核^[6]、He^[4]、氖核、H^[3]或双中子），这些球子以堆积的方式围绕在核心周围。

英文

例如，在金属间化合物^[7]Mg₃₂(Al,Zn)₄₉中发现的（二十面体的）三角形最密堆积各外层中包含的球子数按顺序依次为1、12、32、72。这些数可用方程 $n_0 = (n_i^{1/3} + 1.30)^3 - n_i$ 近似表示，其中 n_0 是在一个外（壳）层中球子的数目， n_i 是核中球子的数目。（这个方程的形式相当于为球子赋予等量的有效体积，常数值反映了表面的小块和外部球子的堆积进入了核心的内部。）这个方程可用来计算核内相继外层中球子的数目，进而获得核子能级的序列数。子壳层（具有特定的角量子数 l ）一旦出现（如组态 $1s1p$ 等）就分配给球子的幔壳层，那些出现二次的（如 $1s$ 和 $2s$ ）就分配给幔壳层和下一个内层，等等。因此，对于上述给定的N或Z = 50的组态，我的解释是：在核心 $(1s^2 1p^6)$ 中有8个中子或质子，另外42个中子或质子在外层 $(2s^2 2p^6 1d^{10} 1f^{14} (1g9/2)^{10})$ 里。

英文

堆积方程的应用基本上导出了梅耶夫人和延森给出的能级序列，但通常是在N或Z值有重叠的范围内填满不同外层的支壳层。例如，支壳层 $3s1/2$ ， $2d3/2$ 和 $1h11/2$ 都在N或Z约为60时开始填充，直到N或Z约为82时才都被填满。

英文

在表1和图1中分别给出了将这种方法应用于幻数后得到的组态。前两个幻数都表示满壳层，第三个幻数（20）则有一个满壳层作为核心和另一个作为幔壳层。其他每一个幻数都包含一个或两个满壳层作为核心，至于它们的幔壳层，在幻数是50的情况下，堆积要求其包含组态为 $(1g9/2)^{10}$ 的支壳层，在幻数为82的状态下，包含 $(1h11/2)^{12}$ 的支壳层，而幻数126则包含 $(1i13/2)^{14}$ 的支壳层，一直至幻数184，不存在N或Z的其他数值，由堆积方程导出的仅包含满壳层的核。

英文

表1. 对于各种幻数的核子组态

N 或 Z	幔壳层	核心或外层核心	内层核心
2	$1s^2$		
8	$1s^2 1p^6$		
20	$2s^2 1p^6 1d^{10}$	$1s^2$	
50	$2s^2 2p^6 1d^{10} 1f^{14} (1g9/2)^{10}$	$1s^2 1p^6$	
82	$3s^2 2p^6 2d^{10} 1f^{14} 1g^{18} (1h11/2)^{12}$	$2s^2 1p^6 1d^{10}$	$1s^2$
126	$3s^2 3p^6 2d^{10} 2f^{14} 1g^{18} 1h^{22} (1i13/2)^{14}$	$2s^2 2p^6 1d^{10} 1f^{14}$	$1s^2 1p^6$

英文

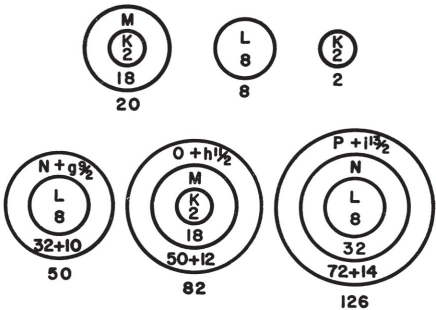


图1 . 原子核的幻数结构

英文

我的结论是，幻数所体现的稳定性来自自由球子组成的单层（2、8）或者双层（20）满壳层，或者对于更大的幻数（50、82、126）和具有核心的层，则幔壳层是由一个满壳层加上一个填满的支壳层构成。

英文

（ 沈乃澍 翻译；厉光烈 审稿）

Character Recognition by Holography

D. Gabor

Dennis Gabor, the inventor of the theory of holography, here suggests an application of the technique, recently improved by the development of the laser, to a long-standing problem in engineering: the automatic recognition of characters, such as printed letters. Holography produces an image of an object based on information contained in a scattered coherent light wave. If one builds up a hologram progressively by scattering light from many possible variants of a single character, then illumination of a character similar to any such variant can be made to produce a visual code easily readable by a machine. Gabor's basic idea, with many modifications, is now commonly used in pattern recognition techniques based on holography. 中文

WAVE-FRONT reconstruction or holography, on which the first report¹ was published in Nature seventeen years ago, had a powerful renaissance in the past years. E. N. Leith and J. Upatnieks², G. W. Stroke³ and others have greatly improved the original method, and showed that it was possible to reconstruct complicated two- and three-dimensional objects, with half-tones, in previously unattainable perfection. The revival of holography owed much of its impulse to the invention of the laser, which made it possible to produce holograms with interferences of the order of 10,000, and thus to make full use of

the information capacity of fine-grain photographic plates. 中文

I wish to show that it has now become possible to harness holography for the solution of one of the most urgent problems of computers and other data-processing devices; the recognition of characters with many variants. 中文

Wave-front reconstruction contains a principle which has not yet been fully exploited. Expressed in a general form: two coherent waves are made to fall simultaneously on a photographic plate, one coming from an object *A*, the other from an object *B*. The photograph links these together in such a way that if the hologram is illuminated by *A* alone, *B* will appear too, and vice versa. So far this principle has been applied in the form that *A* was the object of interest and *B* a light source, usually a simple one, and in the reconstruction the hologram was illuminated by *B*. I now propose to turn this around. Let *A* be a character, such as a printed or hand-written letter or numeral, which can be read by human beings but not by a machine, and let *B* be a combination of point-sources, forming a code-word which can be read by a machine. Produce the hologram by combining *A* and *B*. When *A*, or a character sufficiently close to it is presented to the hologram, with the original illumination, the code-word *B* will flash out. This means that the hologram can act as a translator, or coding device.

中文

The interest of this principle is in the enormous recognition capacity which can be stored in a single hologram, and which one might not perhaps suspect at first sight. I wish to show that with *N* characters to be discriminated, each with *M* variants, the product ***M·N*** can be made of the order of a thousand or even more. 中文

Fig. 1 shows the optics for producing the master hologram, and for using it in the read-out. The recording medium is assumed to be a transparency, such as a microfilm; but reflecting media can also be

used. The hologram is built up by repeated exposures in what may be called “layers”. These are not, of course, physically separated in the emulsion. Each layer corresponds to one of the N characters to be discriminated, with all its M variants, and is marked with one code-word. The layer contains the part-holograms, to be called “engrams” of the variants side by side, with little overlap. Each engram is produced with one direction of illumination, and as the photographic plate is arranged in the rear focal plane of a lens viewing the character, it is a “Fourier-hologram”. This has the advantage that the hologram is translation-invariant, that is to say, independent of the position of the character so long as this appears alone in the window. An engram need not occupy much more area in a photographic plate than would be needed for a good record of the corresponding character, but as a cautious example we will assume 120 engrams, each with a diameter of about 5 mm, on a photographic plate of 50 mm $\times$ 50mm. This is sufficient to record without overlap 30 variants, each in four or six “identical” engrams. Fig. 1 shows how this is achieved.

中文

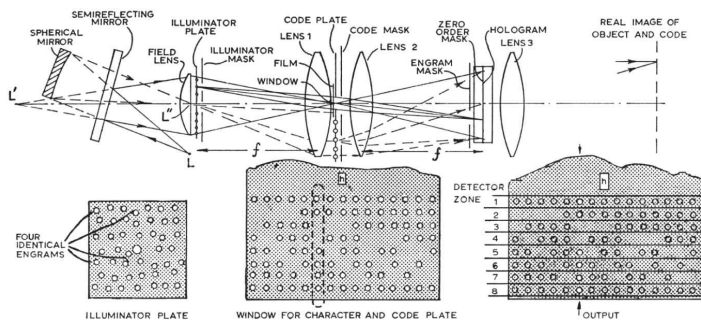


Fig. 1. Apparatus for producing a coding hologram and using it for the read-out.

中文

The light of a laser issues from a point L , and a beam splitter consisting of a spherical mirror and a semi-reflecting mirror produces of this two images L' and L'' . The first of those serves the illuminator; the second, in the centre hole of the illuminator plate, serves the code plate. The illuminator plate, backed by a field lens, consists of a plastic plate embossed with, say, 120 lenticules, and is black outside

the lenticules. These produce 120 point sources which illuminate the window containing the character through a lens 1, which removes the illuminator points into star space. The point sources correspond one-by-one to the engrams. There is a certain advantage in randomizing them slightly. Four identical engrams are taken at a time of any one variant. These are spaced out, as far as possible, to increase the resolving power of the hologram. They are selected with a mask, and a different mask with four holes is used for every variant. 中文

The point source L'' in the centre of the illuminator plate illuminates the code-plate, through the same lens 1, which serves in this area as a field lens. The code-plate, like the illuminator, is an embossed plastic plate, which contains the code-word in the form of groups of luminous points, arranged in one or several arrays. It is advantageous to use self-checking codes, in which every word has the same number of code-points. In the example there are six positions, of which two remain dark and four light up. This code has $6 \cdot 5 / 1 \cdot 2 = 15$ words. Two more positions have been added. There do not contribute to the discrimination of characters, but improve the signal-to-noise ratio, as eight points have to light up for every valid character. 中文

In the making of the master hologram all engrams in one layer are marked, that is to say, exposed simultaneously, with one distinctive code-word, which is selected by a mask. But as each code-word illuminates the whole area of the hologram, a further mask must be used near the plane of the photographic plate, which cuts out the light except in the area of the engrams which are made at any one time. This makes it possible to observe the rule of optimum illumination, which postulates about equal light sums on any engram from the character and from its code-word. 中文

Black-on-white letters are less suitable for discrimination than their negatives, because they have too much in common; all their white area. But this disadvantage can be eliminated by a further mask, in the

plane of the hologram, which cuts out all undiffracted light. By Babinet's principle this turns a character into its negative. Such a mask can be easily made by exposing a photographic plate through a clear window simultaneously to all illuminator points. 中文

After $M \cdot N$ successive exposures of the photographic plate, which add up to a convenient medium density, the master hologram is made by processing and printing it, preferably with an overall gamma of 2, and the print is put back in the original position. In the reading all the point-sources of the illuminator are used, while the whole code-plate is covered up. A lens 3 is used for observation, which produces a real image of the code-plate. If now the recording medium is dragged across the window, whenever a character or a variant appears in it, its code-word will flash up. It is advantageous to arrange in the image plane a mask, which is a replica of the code-plate, with very fine holes, so as to exclude all but the signalling light. This mask, too, can be made photographically. 中文

A method of reading the code-words is to sum up all the light which appears in one zone, corresponding to one position in the code, and guide it to a separate photoelectric detector. Each detector is fitted with a level discriminator, so as to reject spurious signals below a certain level. This method is simple; but it has only moderate discriminating power, because if the characters are not clearly distinct, some light might show up in the same zone in the code-words of other characters. One can reduce this by making the code-words of characters which are not clearly distinct as different as possible. But the maximum of discrimination is achieved by a somewhat more complicated apparatus. In this the image of the code-plate is projected on the screen of an image camera. The code-words flash up at intervals corresponding to the time allotted to each letter, during 10-30 percent of this period. In the time between flashes all code positions are scanned word by word, and points above a certain level

of intensity are transferred to a memory organ, such as a core store. But unless the full number of points appear in a word, the record is erased. If the full number is counted, the code-word is transferred to the computer. 中文

The great discriminating power of the holographic method stems from its high angular resolution. Assume, for example, $N = 35$, $M = 30$, $M \cdot N = 1050$. The group of four engrams corresponding to the character presented to the reader receives $1/30$ of the light, and can diffract about $1/35$ of it, altogether about 10^{-3} of the total. (Not counting, of course, in black-on-white records, the undiffracted light which goes into the zero order.) Of the diffracted light, under the proper conditions, that is to say, when the engrams were taken with about equal light sums from the letter and from the code-word, one-quarter will go into the reconstruction of the code-word. One half appears in the object, another quarter goes into the “twin” image of the code-word, which, however, is washed out by intermodulation with the character, and is useless for recognition. But the useful quarter is concentrated in extremely small solid angles. For example, if four or six identical engrams are spaced out by about 25 mm, the solid angle in which the major part of the light corresponding to a code-point is concentrated will be of the order 10^{-8} . Let the light of, say, 10^{-4} of the total be distributed among ten code-points, this means that 10^{-5} of the light appears in one code-point, in a solid angle which is perhaps 10^{-6} of the solid angle covered by the whole code; a concentration of the order ten. Moreover, this estimate is somewhat pessimistic, because it takes no account of the confirmation of the character by the engrams of slightly different variants in the same layer. 中文

In conclusion, there is good reason to believe that a single hologram may discriminate between all the numerals and the letters of the alphabet, each with 30 variants. 中文

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References:

1. Gabor, D., *Nature*, **161**, 777 (1948); *Proc. Roy. Soc., A*, **197**, 475 (1949); *Proc. Phys. Soc., B*, **64**, 244 (1951).
2. Leith, E. N., and Upatnieks, J., *J. Opt. Soc. Amer.*, **53**, 1377 (1963); **54**, 1295 (1964); **55**, 569 (1965).
3. Stroke, G. W., *Optics of Coherent and Non-coherent Electromagnetic Radiations*, Univ. Michigan (1965), with Falconer, D. G., *Physics Letters*, **13**, 306 (1964); **15**, 283 (1965).

利用全息术的字符识别

盖伯

全息术理论的发明者丹尼斯·盖伯在本文中提出了该技术（最近因激光器的发展而有所改进）的一项应用，即应用于工程技术中长期存在的一个问题：字符（例如印刷字体）自动识别。全息术产生物体的像建立在包含有相干光波散射信息的基础之上。如果将同一个字符各种可能的变形所散射的光递增地制作出一张全息图，那么与任何一个变形相似的字符的照明就能够产生一个便于机器读出的视觉编码。盖伯的基本创意经过多次改进后，现在已经普遍用在基于全息术的图形识别技术中。 [英文](#)

17年前《自然》首次报道^[1]了波前重建，即全息术，近年来这项技术又再次兴起，势头强劲。利思和乌帕特尼克斯^[2]、斯托克^[3]以及其他一些人已经对原来的方法做了重大的改进，并表明有可能利用半色调重建复杂的二维物体和三维物体，并达到过去不能实现的完美程度。激光器的发明在很大程度上推动了全息术的复苏，因为它使利用量级为10,000的干涉产生全息图成为可能，这样也可以充分利用细粒照相干板上的信息容量。 [英文](#)

我要说明的是，现在利用全息术有望解决计算机和其他数据处理装置中最为紧迫的问题之一——对具有多种变形字符的识别。 [英文](#)

波前重建包含了一个尚未被充分应用的原理。通常表现为：两束相干波同时照射在一张照相干板上，其中一束来自物体A，另一束来自物体B。如果全息图单独用A照明，B也会出现，反之亦然，全息图就是通过这样的方式将它们联系在一起的。至今，这个原理已经通过下述方式加以利用：若A是被关注的物体，B是光源（通常是简单的一个单个的光源），在重建中，全息图用B照明。现在我要对此进行一些改动。设A是

一个字符，例如一个印刷的或手写的字母或数字，它可以被人读出，但不能被机器识别，再设 B 是点光源的一个组合，它形成了一个可被机器识别的编码。将 A 和 B 混合便可产生全息图。当 A 或一个与它十分相似的字符呈现在全息图前，并使用原来的照明光照亮时，编码 B 将立刻浮现出来。这表明全息图起到了转换器或编码装置的作用。 [英文](#)

这个原理的价值在于它所具有的巨大的识别容量，并且能存储在单个全息图中，对此人们最初也许不会察觉得到。我要说明的是，要对 N 个字符进行辨别，每个有 M 种变形，其乘积 $M \cdot N$ 能够达到上千甚至更高的量级。 [英文](#)

制作主全息图并利用它进行读取的光学装置如图1所示。假定记录介质是透射型的，例如显微胶片，不过也能够使用反射型介质。通过在“层”（姑且这样命名）上重复曝光而产生全息图。当然，这并不是说乳胶中存在物理上的分离。每一层都对应 N 个字符中的一个字符，每个都具有 M 种变形的待辨别字符，并用一个编码字标记。这个层包含了部分全息图，称为各个变形的“忆迹”，它们并排相连并略微重叠。每个忆迹是用一个方向上的光束照射产生的，又因为照相干板位于观测字符的透镜的后焦平面上，因此是一个“傅里叶全息图”。其优点在于全息图具有平移不变性，换言之，字符只需在窗口中单独出现，而其所处的位置是无关紧要的。与良好地记录一个字符所需要的面积相比，相应的一个忆迹并不需要占用照相干板更大的面积。而作为一个严谨的例子，我们将假设在50毫米×50毫米的照相干板上有120个直径约为5毫米的忆迹，这就足够在无须重叠的方式下记录30个变形，其中每个有4个或6个“同样的”忆迹。图1显示了这是如何实现的。 [英文](#)

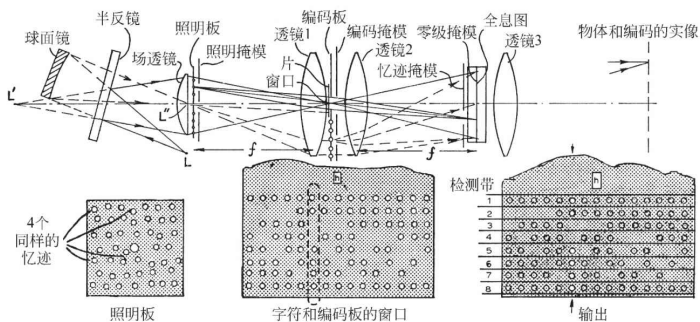


图1：制作编码全息图并将它读出的装置 [英文](#)

激光器的光束从点 L 射出，通过一个包含有一个球面镜和一个半反镜的分束器后产生两个像 L' 和 L'' 。其中第一个像被用作照明光；位于照明板中心孔处的第二个像被用作编码板。照明板在场透镜的背后，其由一片有120个微透镜的模压塑料板构成，在微透镜外为黑色。这些微透镜形成了120个点光源，它们穿过透镜1照射在包含字符的窗口上，使照明点移入了星空。点光源与忆迹一一对应。它们的排列稍有随机性是有利的。当任何一个变形发生时，一次均可获得4个同样的忆迹。为了提高全息图的分辨率，这些忆迹要尽可能地相互远离。用掩模对它们进行挑选，每个变形使用一个不同的带有4个孔的掩模。 [英文](#)

位于照明板中心的点光源 L'' 同样通过透镜1照明编码板，透镜1在这一区域作为场透镜使用。与照明器类似，编码板是一块模压塑料板。它包含的编码字以一群照明点的形式存在，它们排成一个或几个阵列。使用自检编码具有一定的优点，因为其中每个字都具有相同数目的编码点。在这个例子中有6个位置，其中2个始终为暗，另外4个被照亮。这个编码具有的字数为 $(6 \times 5)/(1 \times 2) = 15$ 。已经又增加了2个位置。这对字符的分辨率并没有贡献，但提高了信噪比，因为每个有效的字符必须有8个点被照亮。 [英文](#)

在主全息图的制作过程中，用一个独特的编码字来标记一个层中所有的忆迹，换言之，它们是同时曝光的，而每个编码字的选择取决于掩模。但由于每个编码字都照明了全息图的整个区域，因此必须在靠近照相干板的平面附近再使用一个掩模，它遮去了在任何时刻获得的忆迹区域以外的光。这样就有可能观测到最佳照明的规律，最佳照明要求对于任一忆迹，来自字符和其编码字的光的总和都大致相等。 [英文](#)

相比于其负片，白底黑字的字母不太适合于鉴别，因为它们之间共同的部分即它们所有的白色区域太多。但这一不利条件可以通过在全息图平面中再加一个掩模来消除，这个掩模遮去了所有的非衍射光。根据巴比涅原理，这样可使一个字符转换为它的负片。令所有的照明点通过一个清晰的窗口同时对照相干板曝光就可以很容易地制作出这类掩模。

[英文](#)

照相干板经 $M \cdot N$ 次连续曝光后，增至一个适合介质的光密度，再通

过处理和洗印就制成了主全息图，总伽马值最好为2，并将照片放回原始位置。在读取过程中使用了照明光的所有点源，而整个编码板是被遮盖住的。透镜3用于观测，它产生了一个编码板的实像。这时如果记录介质被拖过窗口，只要有字符或其变形在其中出现，其编码字便会立刻显现出来。在像平面放置一个掩模是有好处的，这个掩模是编码板的复制品，具有很细的孔，因此可以排除信号光外的所有光。这类掩模也能通过照相而制得。 [英文](#)

读取编码字的方法是：将与编码中某一位置相对应的一个带中出现的所有的光相加，并将它导入一个单独的光电探测器。每个探测器与一水平鉴别器相配，以排除低于一定水平的乱真信号。这种方法简单，但只具有一般的鉴别能力，因为如果有些字符没有明显的区别，那么其他字符的编码字的光可能会出现在同一带内。对于那些没有明显区别的字符，可以通过制作尽可能不同的编码字来减少这种情况。但通过更加复杂的装置可以达到最大的鉴别力。在这个装置中，编码板的像投影在相机的屏上。编码字每隔一段时间闪现，占这个周期的10%~30%，而闪现的时间间隔与分配给每个字母的时间相对应。在闪现间隔的时间内，所有的编码位置被逐一扫描，那些高于一定强度水平的点被传送到一个存储元件上，例如磁心存储器。但是直到一个字中全部的点都出现，这个记录才会被清除。如果点的总数被记录下来，那么这个编码字就会被传送到计算机中。 [英文](#)

全息照相方法的高辨别能力来自其角度的高分辨率。例如假定 $N=35$ ， $M=30$ ，则 $M \cdot N=1050$ 。提交给读出器的字符所对应的4个忆迹的组接收到光的1/30，其中约1/35会发生衍射，因此全部的光约占总数的1/10³。（当然，没有将白底黑字的记录计算在内，因为其非衍射光的量级接近于零。）也就是说，在适当的条件下，当忆迹从字符中和从编码字中接收到的光近乎相等时，衍射光的1/4将进入编码字的重建中去。此外，一半出现在物体中，另外的1/4进入编码字的“孪生”像中，然而，由于这部分与字符交互调制，并且对于识别没有帮助，所以被消除了。但是有用的1/4集中在极小的立体角中。例如，如果4个或6个同样的忆迹彼此之间的距离间隔约为25毫米，那么与一个编码点相对应的光将大部分集中在量级为10⁻⁸的立体角内。也就是说，占总量1/10⁴的

光分布在10个编码点上，这意味着一个编码点上出现的光为 $1/10^5$ ，并且集中在一个可能为布满全部编码的 10^{-6} 的立体角中，汇集度为10。此外，这种估计有些悲观，因为它忽略了在同一层中略有差异的变形忆迹对字符的证实。 [英文](#)

总之，我们完全有理由相信，单个全息图可以在所有的数字和字母表中的字母之间进行辨别，其中每个有30个变形。 [英文](#)

（沈乃澍 翻译；熊秉衡 审稿）

A Dense Packing of Hard Spheres with Five-fold Symmetry

B. G. Bagley

Crystals are forbidden from having five-fold symmetry on geometric grounds: it is impossible to pack pentagons without gaps. The discovery in 1984 of a metal alloy with apparent ten-fold symmetry seemed to challenge that idea, but this so-called quasicrystal proved to lack true crystallinity. This paper from B. G. Bagley describes, two decades earlier, another way to create five-fold symmetry from a dense, infinitely extended packing of spheres. The packing is not periodic in three dimensions, however, but has a definite centre. The following year, an example of Bagley's scheme was reported for virus particles. Bagley also cites five-fold-symmetric clusters proposed by Desmond Bernal to exist in simple liquids, which were later invoked as possible nuclei of incipient quasicrystals. [中文](#)

SUPPOSE a plane of hard spheres is constructed such that the spheres form concentric pentagons with an odd number of balls per pentagon side. A second plane of hard spheres is now constructed such that the spheres form concentric pentagons with an even number of spheres per pentagon side. If this second plane is placed in intimate contact with the first, with their five-fold axes coincident, there results a layer

which, within the plane of the layer, can be continuously packed to infinity (Fig. 1). Identical layers can then be stacked one on another, with their five-fold axes coincident, to give an infinite packing along the five-fold axis. An infinite structure can thus be constructed the nucleus of which is a pentagonal dipyramid of seven spheres. 中文

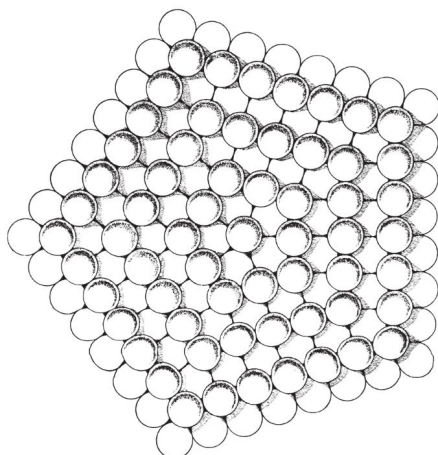


Fig. 1. A layer of hard spheres based on a packing sequence of concentric pentagons. 中文

Following the foregoing packing sequence with polygons other than the pentagon results in other, well-known structures. The same sequence with squares yields cubic close packing¹ and, with hexagons, primitive hexagonal. A difficulty arises when attempts are made to apply the exact sequence to triangles, because concentric triangles with an even (or odd) number of spheres per side cannot be made coplanar. It is important that, of these polygons, only the pentagon cannot form a regular tessellation and therefore, although it can be packed to infinity, it has a unique axis, the single five-fold rotation axis. 中文

An alternative way of generating the same pentagonal structure is as follows: Construct n ($n = 1, 2, 3, \dots \infty$) pentagonal pyramidal shells of hard spheres such that each face is an equilateral triangle of side length n (spheres). If shell 1 is placed in the cavity of shell 2 there results a pentagonal dipyramid of seven atoms. Likewise when shell 3

is placed on the structure there results a pentagonal dipyramid of twenty-three spheres. In fact, as each subsequent shell is placed on the growing structure there always results a pentagonal dipyramid bounded by close-packed planes, each face of which is an equilateral triangle with n (shell number) spheres to a side. This pentagonal dipyramid consists of five distorted tetrahedral the edges parallel to the five-fold axis being expanded by 5.15 percent. Within each tetrahedron the structure is body-centred orthorhombic with cell dimensions chosen such that the pentagonal dipyramid faces will be close packed and two adjacent tetrahedra will be joined by a coincidence boundary. These conditions yield a body-centred orthorhombic cell with dimensions (diameter of sphere = 1.000), $a = 1.000$, $b = \cot 36^\circ = 1.3764$, $c = (2^2 - \csc^2 36^\circ)^{1/2} = 1.0515$. Thus this pentagonal structure has a density independent of position of 0.72357. This density is slightly lower than that for close packing (0.74048), but higher than body-centred cubic (0.68017) or icosahedral shell packing (0.68818) (ref. 2). The co-ordination is 10 at a distance of 1.000 and 2 at a distance of 1.052. This structure is an example of G_3^1 type symmetry, that is, a one-dimensionally periodic group in three dimensions, and its symmetry group is $5mP2ml$ (Niggli's³ nomenclature). 中文

Structures which have the symmetry described here have been observed experimentally. Gedwill, Altstetter and Wayman⁴, using optical microscopy, observed five-fold symmetry in cobalt crystals produced by the hydrogen reduction of cobaltous bromide. Wentorf⁵, also using optical microscopy (external morphology), observed five-fold symmetry in synthetic diamonds. Ogburn, Paretzkin and Peiser⁶, using X-rays, found pentagonal symmetry in copper [110] dendrites grown by electrodeposition. The most striking examples, however, are the sub-micron whiskers of nickel, iron and platinum grown from the vapour by Melmed and Hayward⁷. These whiskers, 50-200 Å in diameter, had a five-fold rotational symmetry observed by field

emission microscopy. The five-fold symmetry was found not to be limited to the surface, as no change in symmetry was observed in the continuous reduction in length of several iron whiskers. 中文

In all these cases the structure was explained as a quintuple twin ((111) twinning plane) with five face-centred cubic individual crystals about a common [110] axis, the $7^{\circ}20'$ difference between $5 \times 70^{\circ}32'$ and 360° being made up with lattice strain or imperfections. It is unlikely, however, that a twinning mechanism could generate a structure having the small size (50–200 Å) and atomic perfection (at the five-fold axis) of Melmed and Hayward's⁷ whiskers. On the other hand, it appears that the formation of a pentagonal dipyrmaid nucleus and its subsequent growth is a more probable and simpler mechanism for the formation of this structure. Furthermore, if a twinning mechanism were responsible for the five-fold symmetry one would expect [110] to be an observed whisker orientation in normal, non-pentagonal, whiskers. This is indeed the case for nickel and platinum, but the observed orientation for face-centred cubic iron is [100] (ref. 8). 中文

It is also to be noted that the pentagonal nucleus for the structure described here has the same form as one of the configurations which has been proposed as an important element of liquid structure by Bernal^{9,10}. It is evident from the foregoing discussion that crystallization can occur by the growth of such a configuration. 中文

I thank Profs. F. C. Frank, C. S. Smith, and D. Turnbull for their advice, and the Xerox Corporation for a fellowship. This work was supported in part by the Office of Naval Research under contract *Nonr* 1866 (50), and by the Division of Engineering and Applied Physics, Harvard University. 中文

B. G. Bagley: Division of Engineering and Applied Physics, Harvard University, Cambridge, Massachusetts.

References:

1. Coxeter, H. S. M., *Illinois J. Math.*, **2**, 746 (1958).
2. Mackay, A. L., *Acta Cryst.*, **15**, 916 (1962).
3. Niggli, A., *Zeit. Krist.*, **111**, 288 (1959).
4. Gedwill, M. A., Altstetter, C. J., and Wayman, C. M., *J. App. Phys.*, **35**, 2266 (1964).
5. Wentorf, R. H., jun., in *The Art and Science of Growing Crystals*, edit. by Gilman, J. J., 192 (Wiley, New York, 1963).
6. Ogburn, F., Paretzkin, B., and Peiser, H. S., *Acta Cryst.*, **17**, 774 (1964).
7. Melmed, A. J., and Hayward, D. O., *J. Chem. Phys.*, **31**, 545 (1959).
8. Melmed, A. J., and Gomer, R., *J. Chem. Phys.*, **34**, 1802 (1961).
9. Bernal, J. D., *Nature*, **183**, 141 (1959).
10. Bernal, J. D., *Nature*, **185**, 68 (1960).

具有五重对称性的硬球的密堆积

巴格利

根据几何学原理，晶体不能具有五重对称性：做五边形堆积而不产生空隙是不可能的。1984年人们发现一种金属合金具有明显的十重对称性，这一发现似乎是对上述观点的挑战，但是后来发现这个所谓的准晶体缺乏真正的晶体性质。巴格利的这篇文章发表于此前20年，文中他介绍了另外一种利用无限外延密堆积小球而构建出五重对称结构的方法。然而，这种堆积在三维空间中不具有周期性，但是却具有一个明确的中心。第二年，人们在病毒粒子中发现了一个巴格利方案的实例。巴格利还引用了德斯蒙德·贝尔纳提出的、存在于简单液体中的五重对称性团簇结构，而后来这被认为是初期准晶体的晶核。 [英文](#)

假定如此构建一个硬球的平面，使若干硬球形成许多同心五边形，且每个五边形边上的硬球数为奇数。而第二个硬球的平面虽也由硬球构成同心五边形，但每个五边形边上的硬球数为偶数。如果将第二个硬球平面与第一个硬球平面紧密接触，且使它们的五重轴一致，这样就形成了一个在层的平面内可以无限连续堆积的硬球层（如图1所示），那么相同的这些层在五重轴一致的方向上可以连续地堆积，这样就可以沿着五重轴的方向形成一个无限堆积。一个无限堆积的结构也因此被构建出来，这个结构的核是由7个球构成的五边形双棱锥体。 [英文](#)

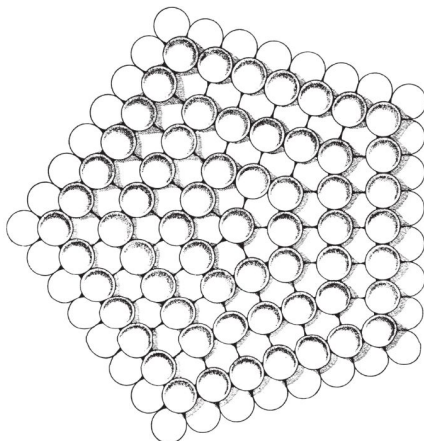


图1．一个基于同心五边形堆积序列的硬球层 英文

接着如果将上述五边形的堆积序列换成其他多边形堆积序列，那么我们就可以得到另外一些大家所熟知的结构。例如，正方形按相同序列堆积便可得到立方密堆积^[1]，六边形按相同序列堆积则可得到简单的六方密堆积。但是，人们在试图做一个精确的三角形序列时出现了困难，因为在共面上不能形成每边具有偶数（或奇数）个球的同心的三角形。重要的是，在这些多边形中，只有五边形不能形成规则的镶嵌，因此，尽管它能无限堆积，却只具有一个特殊的轴，即唯一的五重旋转轴。

英文

产生相同的五边形结构的另一种方法如下：构建 n ($n = 1, 2, 3, \dots$) 的五边形棱锥的硬球壳层，使它的每个面都是一个边长为 n （球）的等边三角形。如果将壳层1置于壳层2的腔体内，结果就形成了一个具有7个原子的五边形双棱锥体。同样，将壳层3置于上述结构上时，它就形成了一个23个球的五边形双棱锥体。实际上，当每个次级壳层置于这种生长的结构上，总可形成一个以密堆积平面为界面的五边形双棱锥体，其中每个面都是边长为 n 个（壳层数）球的等边三角形。这种五边形双棱锥体是由五个畸变的四面体组成的，它的边平行于向外扩展5.15%的五重轴。每个四面体内都是体心正交晶结构，具有的单胞尺度能使五边形双棱锥体的面可以呈密堆积，且两个相邻的四面体通过重合边界连接在一起。这些条件所产生的体心正交单胞的尺度是（球的直径 = 1.000）： $a = 1.000$ 、 $b = \cot 36^\circ = 1.3764$ 、 $c = (2^2 - \csc^2 36^\circ)^{1/2} = 1.0515$ 。因此，这个五边形结构具有的密度值为

0.72357，它与位置无关。这个密度比密堆积密度（0.74048）稍低，但高于体心立方堆积（0.68017），或二十面体的壳层堆积（0.68818）（参考文献2）。在距离为1.000时，配位数为10，在距离为1.052时，配位数就为2。这种结构是 G_3^1 型对称性的一个例子，也就是说，在三维中的一维的周期群，其对称群为 $5mP2ml$ （尼格利^[3]的命名法）。

英文

本文描述的对称性结构已在实验中观测到。格德威尔、阿尔特施泰特和韦曼^[4]用光学显微镜观测到了由氢还原溴化钴所产生的钴晶体的五重对称性。温托夫^[5]也用光学显微镜（外形貌学）观测到了合成金刚石的五重对称性。奥格本、帕雷茨金和派泽^[6]用X射线发现了通过电沉积生长的铜[110]枝晶的五角对称性。然而，最显著的例子是梅尔梅德和海沃德^[7]利用蒸汽生长出镍、铁和铂的亚微米晶须。这些晶须的直径为50埃~200埃，通过场发射显微镜观测到其具有五重旋转对称性。这种五重对称性不只限于表面，因为在一些铁晶须的连续剥离的过程中，并没有观测到对称性的变化。

英文

在所有这些情况下，该结构都解释为五重孪晶（（111）孪晶平面），即在共同的[110]轴的周围有5个面心立方的晶体， $5 \times 70^\circ 32'$ 与 360° 之间的 $7^\circ 20'$ 之差是点阵应变或欠完美性引起的。然而，不同的是孪晶机制未必能产生梅尔梅德和海沃德^[7]晶须的小尺寸（50埃~200埃）结构以及在五重轴上的原子完美性。另一方面，五边形双棱锥体晶核的形成以及其随后的生长，也许是这种结构形成的更可能且更简单的机制。而且，如果孪晶机制是造成五重对称性的原因，可以预期在通常的、非五边形的晶须中法向取向应为[110]。这确实符合镍和铂的情况，但在面心立方的铁中观测到的方向却是[100]（参考文献8）。

英文

还应注意到，本文所述结构的五边形核与由贝尔纳^[9,10]提出的液体结构的重要组态之一具有相同的形式。从上述讨论中我们可以明显得出，这类组态在生长的过程中能够产生结晶。

英文

我要感谢弗兰克教授、史密斯教授和特恩布尔教授提供的意见，同时也感谢施乐公司提供的科研经费。这项研究的部分工作得到了海军研

究办公室（合同为Nonr 1866（50））以及哈佛大学工程与应用物理学院的支持。 英文

（沈乃澍 翻译；赵见高 审稿）

Reconstruction of Phase Objects by Holography

D. Gabor *et al.*

In 1948, Hungarian physicist Dennis Gabor reported in *Nature* a kind of three-dimensional imaging process which he called holography. He developed the idea initially in connection with the optics of electron beams, although he later generalized it to light. Holography relies on the interaction of the phases of reflected rays, but as Gabor and his coworkers say here, that phase information might appear to be lost in photographic images which merely record brightness of the beams. They show, however, a way to reconstruct both the phases and the amplitudes of the beams using optical holography, and thus to obtain all the available information about the object from which the rays are scattered. [中文](#)

THE principle of wave-front-reconstruction imaging, first described by one of us in 1948 (refs.1–3), has recently resulted in spectacular advances, notably in the form of three-dimensional “lensless” photography and imaging, with both macroscopic and microscopic objects^{3–8}. Excellent images have been obtained in a number of variations of the basic method, notably when the objects used were “half-tone” intensity objects, or transparencies, rather than “phase” objects. [中文](#)

“Phase” objects may be of a primary interest in a number of holographic applications, notably in microscopy, and in several other applications, where phase rather than amplitude variations in the light field may be predominantly characteristic of the physical phenomena under investigation, for example, in work with wind tunnels and in acoustical applications. [中文](#)

As holograms are recorded on photographic emulsions which register only intensities, not phases, one might easily believe that a hologram is not a full substitute for a real object. Indeed, the total wave-front which issues from a hologram in the reconstruction cannot be the same as the original wave-front emitted by the object, because one half of the information is missing. In order to obtain the total information one requires two holograms, which are in sine-cosine relation to one another. Two such “complementary” or “quadrature” holograms have been used in the “total reconstruction microscope” by one of us⁹. Adding up the wave-fronts issuing from two such holograms, one obtains in the reconstruction the original wave-front, and nothing else, except a uniform background. [中文](#)

However, somewhat paradoxically, the original wave-front is also contained in the modified wave-front diffracted in the reconstruction by a single hologram. The incompleteness shows itself in the fact that this wave-front is mixed up with an additional wave, which appears to issue from a “conjugate object”. But the two partial wave-fronts can be separated by various methods, the simplest of which is using a skew reference beam at an angle to the plate, in the taking of the hologram. The information-theoretical paradox that an incomplete record contains the full information in a retrievable form is explained by the fact that there is a loss of one half of the definition. This, however, is as good as unnoticeable in almost all present-day applications of holography. [中文](#)

Consequently, since one of the two (or more) waves diffracted by the

hologram in the reconstruction process contains information on both the amplitude and the phase distribution in the object, both the phase and the amplitude information may be extracted from the reconstructed wave-front, for example, by suitable “filtering” of the aerial reconstructed images, or diffraction patterns, before the final image is recorded on a photographic film. In essence, the image-forming wave-fronts reconstructed from holograms are indistinguishable from the wave-front which would be obtained from an ideal lens or mirror looking directly at the object, when it is possible to form an image in the ordinary “one-step” imaging, for example, in microscopy. It has therefore been clear to us for some time that we may display the phase in the holographically reconstructed images of “phase” objects, when necessary, with the aid of any one of the several well-known methods^{10,11} (for example, phase contrast, interferometry, Foucault or Schlieren methods) used to display the phase variations in the form of amplitude variations, as used in microscopy and other phase measuring applications in optics.

中文

Because of the great present interest in holography, and because some of our recent advances seem to indicate a good likelihood that high resolutions may indeed be attainable in microscopy at very short wave-lengths (for example, X-rays), it may be of interest to demonstrate that phase-preserving imaging and “phase-contrast” image reconstruction may indeed be readily achieved in holography, using single holograms. 中文

As one example of the “phase-preserving” reconstruction of the image of a phase object, we have used the arrangement shown in Fig. 1. The phase object used is shown (barely visible) in Fig. 2a, and an enlarged transmission two-beam interferogram of the object is shown in Fig. 2b. The phase object was formed by photographing the word “phase” and the letter “ ϕ ” on a Kodak 649F plate, and by bleaching the emulsion

(using Kodak chromium intensifier as the bleacher). It is well known that photographic emulsions will shrink with the density of the exposure. (Typical emulsion shrinkage with exposure factors, 1, 2, 3, 4, is shown in Fig. 2c.) The phase object was recorded by projecting an image on to the plate deliberately slightly out of focus, in order to avoid steep gradients at the edges of the letters. (The amount of shrinkage shown in Fig. 2b was achieved in a 20-sec exposure, with a 75 W bulb, at $f/11$, in 1:1 imaging in the enlarger, and suitable bleaching.) 中文

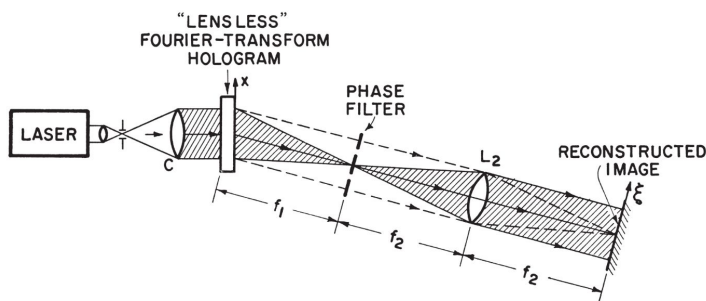


Fig. 1. Modified Fourier-transform holographic image-reconstruction arrangement, permitting “phase-contrast” detection and imaging of phase objects. The distance f_1 is equal to the distance of the object, respectively point-reference, from the hologram in the “lensless” recording of the Fourier-transform hologram^{12,13}; “Conventional” Fourier-transform reconstruction of the images from the Fourier-transform holograms is obtained in the absence of the “phase filter”. (The geometrical magnification obtained in Fourier-transform holographic imaging is equal to the ratio f_2/f_1 . An additional magnification factor equal to λ_2/λ_1 is obtained, when the reconstructing wave-length λ_2 exceeds the recording wave-length λ_1 . In this work, $f_1 = 415$ mm, $f_2 = 600$ mm, $\lambda_2 = \lambda_1 = 6,328$ Å) 中文



Fig. 2a. Direct (not holographic) image of phase object used in this work, showing degree to which a “pure” phase object was obtained by suitable bleaching of a Kodak 649F emulsion (see text, and Fig. 2b). The object is the word “phase” and the letter “φ” (the word phase being 20 mm long). The slight contrast detectable is due to some slight defocusing, and some residual absorption in the plate 中文

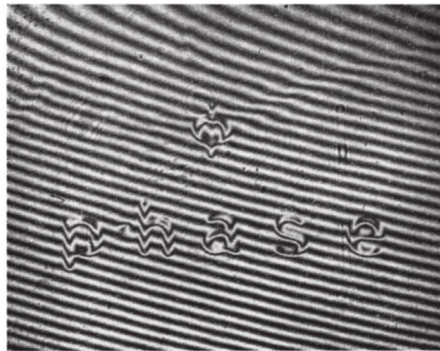


Fig. 2b. Two-beam single-pass interferogram ($6,328 \text{ \AA}$) of the phase object used in this work. The hologram of this phase object was recorded in the “lensless” Fourier-transform hologram recording arrangement according to ref. 12 中文

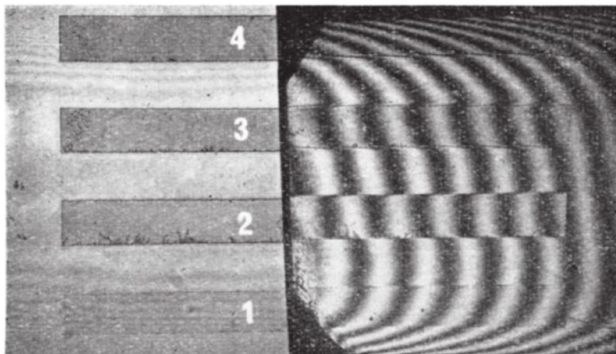


Fig. 2c. Two-beam single-pass interferogram ($6,328 \text{ \AA}$), illustrating the amount of emulsion shrinkage and corresponding phase variation achievable in a Kodak 649F emulsion with four different exposures (in ratios $\times 1$, $\times 2$, $\times 3$, $\times 4$), and suitable bleaching with Kodak chromium image intensifier, used to obtain almost pure “phase objects”, with minimum residual absorption [中文](#)

The hologram of the phase object was recorded in the “lensless Fourier-transform” hologram recording arrangement, first described by one of us^{12,13}, in which the spherical waves originating from the various object points are made to interfere with a “single” spherical reference wave, originating from a source “point” in the mean plane next to the object. A reference wave of a radius $f_1 = 415 \text{ mm}$ was used in the recording. (We may note that the “lensless” recording of the hologram permits storage of the information about the phase distribution in the object without introducing any other optical elements between the object and the emulsion, thus avoiding any extraneous scattering, which might reduce the fidelity and sensitivity of the method.) [中文](#)

The images reconstructed from the “lensless Fourier-transform” hologram are shown in Figs. 3, 4 and 5. Fig. 3 shows a Fourier transform reconstruction, without filtering, obtained by simply projecting a plane monochromatic ($6,328 \text{ \AA}$) wave through the hologram, and by recording one of the side-band images in the focal plane of a $f_2 = 600 \text{ mm}$ lens. Unlike the reconstruction-imaging of intensity or amplitude objects, the reconstructed image of the phase object in Fig. 3 shows no amplitude contrast, because of the “pure” phase nature of the object. [中文](#)

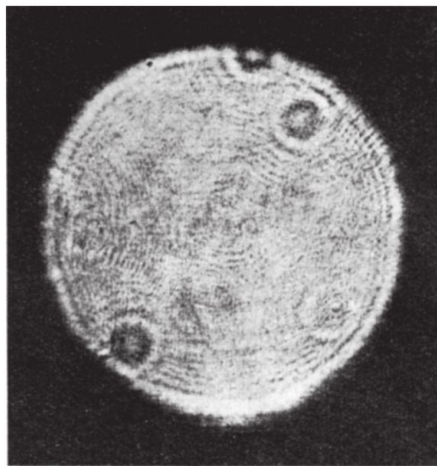


Fig. 3. Reconstructed image, obtained by Fourier-transform reconstruction in the arrangement of Fig. 1, without the use of any phase-contrast enhancement. (The “lensless” Fourier-transform recording of the hologram of the object was obtained according to ref. 12.) The image shown here is characterized by an almost complete absence of any amplitude contrast in the phase-portions of the image (the various interference effects are spurious, and are caused mainly by imperfectly clean reconstructing optics). It may be noted that excellent imaging is obtained under similar conditions when the original objects are amplitude or intensity objects^{12,13}, rather than pure phase objects [中文](#)

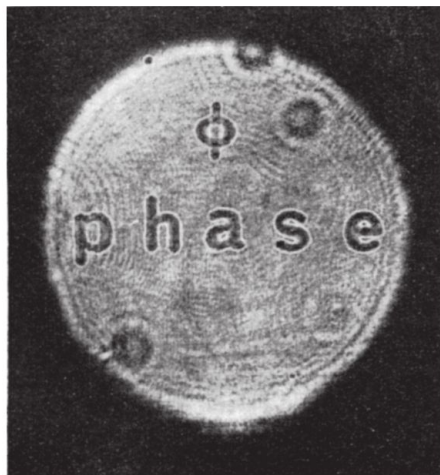


Fig. 4a. Reconstructed image of phase object, obtained with “phase-contrast” enhancement by defocusing (here towards the L_2 lens of Fig. 1 by $-f_2/4$, with $f_2=600$ mm). The length of the word in the object was 20 mm (in the image, it is 30 mm, because of the f_2/f_1 magnification (see Fig. 1)) [中文](#)

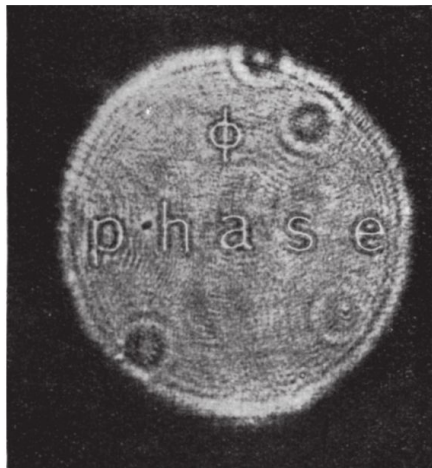


Fig. 4b. Reconstructed image of phase object, with “phase-contrast” enhancement, obtained by defocusing (here, out of focus, away from the lens L_2 by $+f_1/4$) 中文

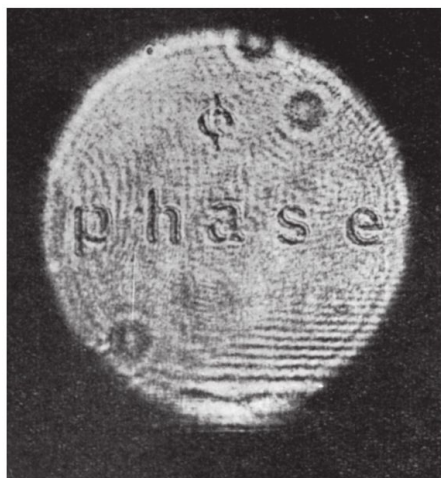


Fig. 4c. Reconstructed image of phase object, with phase-contrast enhancement obtained by using a phase-contrast filter (the corner of one of the rectangular phase strips, shown in Fig. 2c) in the arrangement of Fig. 1. (Here, the interference effects are spurious, and due to some imperfect cleanliness in the reconstruction optics) 中文

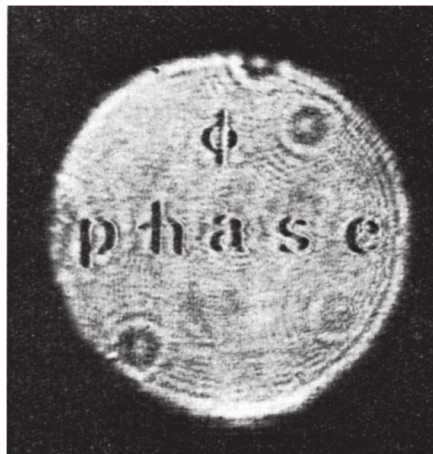


Fig. 4d. Reconstructed image of phase object, with phase-contrast enhancement, obtained with a Foucault knife-edge used in the phase-filter plane of Fig. 1 中文

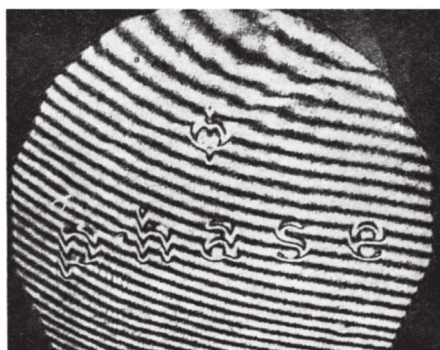


Fig. 5. "Hologram of the hologram." Two-beam single-pass interferogram ($6,328 \text{ \AA}$ laser light) of the interference pattern between the reconstructed aerial image and a plane reference beam. Comparison of the image-interferogram shown here with the similarly obtained object-interferogram of Fig. 2b demonstrates that phase-distribution in the object is indeed preserved and completely reconstructed in Fourier-transform wavefront-reconstruction imaging, using a modified "phase-contrast" enhancing arrangement, such as that illustrated in Fig. 1. (We may note that phase preservation and phase-enhancing reconstruction apply to holograms recorded at one wave-length, and reconstructed in a second wave-length, for example, when λ_1 is in the X-ray domain and λ_2 in the visible-light laser domain) 中文

Figs. 4 and 5 show well-contrasted images of the phase object, obtained by a number of the well-known phase filtering or phase-contrast methods, in which the phase variations are made visible in the form of amplitude (that is, intensity) variations in the image.

中文

Figs. 4a and b show the reconstructed images, obtained by a

“defocusing” phase-contrast enhancement, in a Fourier-transform reconstruction arrangement, as in the sharply focused Fig. 3, but now by recording the images together slightly ($\pm 1/4 f_2$ at $f/24$) out of focus, with respect to the in-focus image of Fig. 3. 中文

Fig. 4c shows an in-focus image, in which the phase-contrast enhancement was obtained in the filtering arrangement shown in Fig. 1, with the help of the corner of a phase-contrast filter (also recorded photographically, and bleached, similarly to the object recording already described here). 中文

Fig. 4d shows an in-focus image, with “phase-contrast” enhancement obtained in the filtering arrangement of Fig. 1, with the help of a Foucault knife-edge filter (at right angles to the word “phase”). 中文

Fig. 5 shows a two-beam interferogram of the reconstructed aerial image, formed by interference of the aerial image with a plane wave (in a suitable beam-splitting arrangement): by comparing the interferogram of the phase object (Fig. 2b), the degree of phase preservation and of fidelity of “phase-preserving” reconstruction may be readily assessed. 中文

It is clear from a comparison of the images and interferogram of the image, of Fig. 4 and of Fig. 5, with the phase object and object-interferogram of Fig. 2, that the phase-distribution in the phase object was not only retrievably recorded in the hologram, but also that the phase in the image of the phase object can be readily displayed as an amplitude (respectively intensity) in the reconstructed image, with the aid of phase-contrast or other image-filtering methods, including interferometry of various types. We may note that there is some indication that holograms of phase objects, recorded with a 1/1 ratio of reference/diffracted field intensity (rather than the about 5/1 used here), appear to display some noticeable “phase-contrast”

enhancement simply in the focus of the “conventional” Fourier-transform reconstruction arrangement. 中文

We thank R. C. Restrict for his advice. This work was supported in part by the U.S. National Science Foundation and the U.S. Office of Naval Research. 中文

(208, 1159-1162; 1965)

D. Gabor: F.R.S., Imperial College of Science and Technology, London.

G. W. Stroke, D. Brumm, A. Funkhouser and A. Labeyrid: University of Michigan, Ann Arbor, Michigan.

References:

1. Gabor, D., *Nature*, **161**, 777 (1948).
2. Gabor, D., *Proc. Roy. Soc., A*, **197**, 475 (1949).
3. Gabor, D., *Proc. Phys. Soc., B*, 244 (1951).
4. Leith, E. N., and Upatnieks, J., *J. Opt. Soc. Amer.*, **53**, 1377 (1963).
5. Leith, E. N., and Upatnieks, J., *J. Opt. Soc. Amer.*, **54**, 1295 (1964).
6. Leith, E. N., Upatnieks, J., and Haines, K. A., *J. Opt. Soc. Amer.*, **55**, 981 (1965).
7. Stroke, G. W., *Optics of Coherent and Non-Coherent Electromagnetic Radiations* (Univ. of Michigan, first ed., May 1964; second ed., March 1965).
8. Stroke, G. W., and Falconer, D. G., *Phys. Letters*, **13**, 306 (1964); **15**, 283 (1965); with Funkhouser, A., *Pyhs. Letters*, **16**, 272 (1965); with Restrict, R., Funkhouser, A., and Brumm, D., *Phys. Letters*, **18**, 274 (1965); *App. Phys. Letters*, **7**, 178 (1965).
9. Gabor, D., with Goss, W. P., British Patent No. 727, 893/1955, application date July 6, 1951.
10. Zernike, F., *Physica, Haag*, **1**, 43 (1934); *Physik. Z.*, **36**, 848 (1935); *Z. Techn. Physik.*, **16**, 454 (1935).
11. Francon, M., *Le Contraste de Phase en Optique et en Microscopie* (Revue d'Oplique, Paris, 1950).
12. Stroke, G. W., *App. Phys. Letters*, **6**, 201 (1965).
13. Stroke, G. W., Brumm, D., and Funkhouser, A., *J. Opt. Soc. Amer.*, **55**, 1327 (1965).

用全息术实现的相位物体的重建

盖伯等

匈牙利物理学家丹尼斯·盖伯于1948年在《自然》上发表了一篇关于一种三维成像过程的报道，他把这种过程称作全息术。他提出的这个想法最初与电子束光学有关，但是后来他将其推广至光学。全息术依赖于反射光线相位的相互作用，但是正如盖伯及其同事们在本文中所说，在利用照相术得到的影像中相位信息似乎会丢失，这些影像记录到的只是光束的亮度。然而他们展示了一种能够通过光学全息术同时重建光束相位和振幅的方法，并通过这种方法获得了有关散射光线的物体的全部有效信息。 [英文](#)

1948年，笔者之一首次描述了波前重建成像的原理（参考文献1~3），最近这个原理产生了惊人的进展，在宏观和微观物体的三维“无透镜”照相术和成像中尤其明显^[3-8]。通过对基本方法做许多改进，人们已经获得了极好的图像，当所用的物体不是“相位”物体而是“半色调”强度物体或透明物体时，效果更为显著。 [英文](#)

在许多全息的应用中，尤其是在显微术以及其他几种应用中，“相位”物体可能是首选，其中所研究物理现象的主要特征可能是光场的相位变化，而非振幅变化，例如在风道的研究和声学的应用中。 [英文](#)

由于全息图是用照相感光乳胶记录的，且该乳胶记录的只是强度，而非相位，因此人们或许很容易相信全息图并不是一个实物的完全替代。实际上，由重建得到的全息图产生的总的波前并不等同于由物体发射的原始的波前，因为有一半的信息丢失了。为了获得全部信息，我们需要两个彼此之间是正弦-余弦关系的全息图。这样两个“互补的”或“正交的”全息图已被笔者之一^[9]用于“完全重建显微术”中。把这样的两个全息图产生的波前相加，我们就得到了重建过程中的原波前，除此以外仅

有均匀的背景。 [英文](#)

然而，有些自相矛盾的是，原始的波前也包含在修正波前中（修正波前是单个全息图在重建中通过衍射得到的）。实际上这种不完整性本身表明，波前中混合了一个似乎由“共轭物体”产生的附加波。但是这两个部分波前可用多种方法分离，其中最简单的方法是在记录全息图的过程中，使用与感光板呈一定角度的偏斜参考光束。一个不完整的记录包含并可以恢复得到完整的信息，这种信息-理论的矛盾可用精确度损失了一半的事实来解释。然而，在目前所有全息图的应用中这一点几乎没有引起人们的注意。 [英文](#)

因此，既然在重建过程中通过全息图衍射得到的两个（或多个）波中，有一个包含了物体中振幅和相位分布的信息，那么相位和振幅的信息或许都可从重建的波前中提取出，例如，在感光胶片上记录下最终图像之前，对存在于空中的重建图像或衍射图样进行适当的“滤波”。本质上，从全息图重建形成的图像，其波前与从一个直接对准物体的理想透镜或镜子得到的波前几乎完全相同，在这种情况下像是通过通常的“一步”成像形成的，例如显微镜中的成像。因此，不久之前我们已经清楚，我们可以在“相位”物体的全息重建图像中显示相位，必要时，可从人们熟知的方法^[10,11]（例如相衬法、干涉测量法、傅科法或纹影法）中任意选取一种以振幅变化的形式来呈现相位变化，就像在显微术中和光学中其他相位测量应用中所使用的方法一样。 [英文](#)

由于目前人们对全息术有很大的兴趣，并且我们最新取得的一些进展似乎表明在波长很短（例如X射线）的情况下可使显微镜得到非常高的分辨率，因此似乎有必要给出以下说明：利用全息术，使用单个全息图或许就可轻易实现保持相位的成像过程及“相衬”图像重建。 [英文](#)

我们使用图1所示的装置，作为一个相位物体图像的“相位保持”重建的例子。所用的相位物体如图2a所示（勉强可见），图2b显示的是物体放大的透射型双光束干涉图。将单词“phase”和字母“ φ ”拍摄在一张柯达649F干板上，并漂白感光乳胶（使用柯达铬增强剂作为漂白剂）从而制得了相位物体。众所周知，感光乳胶将随着曝光强度的增加而收缩。（图2c为在曝光因子为1、2、3、4时，典型的感光乳胶的收缩。）为了

避免字母边缘斜度过大，相位物体是通过将像投影在故意稍稍偏离焦点的胶片上来记录的。（图2b中所示的收缩量是用75瓦的灯泡在 $f/11$ 和在20秒的曝光下以1：1在放大机内成像并作适当漂白而获得的。） 英文

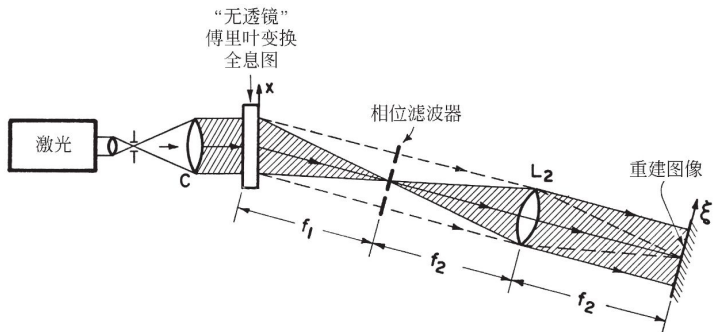


图1．改进型的傅里叶变换全息像重建装置，可以进行相位物体的“相衬”检测和相位物体的成像。在傅里叶变换全息图的“无透镜”记录中，距离 f_1 分别等于物体和点参考光源到全息图间的距离^[12,13]。从傅里叶变换全息图得到的像的“传统的”傅里叶变换重建是在无“相位滤波器”的情况下得到的。（在傅里叶变换全息成像过程中获得的几何放大倍率等于 f_2/f_1 。当重建波长 λ_2 超过记录波长 λ_1 时，得到的附加放大倍数因子等于 λ_2/λ_1 。在本文中， $f_1 = 415$ 毫米， $f_2 = 600$ 毫米， $\lambda_2 = \lambda_1 = 6,328$ 埃。） 英文



图2a. 在本研究工作中使用的相位物体的直接（不是全息的）图像，这是用柯达649F感光乳胶（见正文和图2b）进行适当漂白得到的“纯”相位物体的程度。该物体是单词“phase”和字母“ ϕ ”（单词“phase”长20毫米）。可以检测到的微弱衬度是由于轻微的散焦以及干板上一些剩余吸收而产生的。 英文

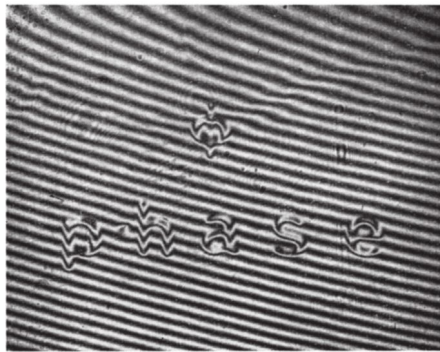


图2b. 本研究工作中所使用的相位物体的双光束单通干涉图（6,328埃）。这个相位物体的全息图是用参考文献12中记录的“无透镜”傅里叶变换全息图记录装置进行记录的。 [英文](#)

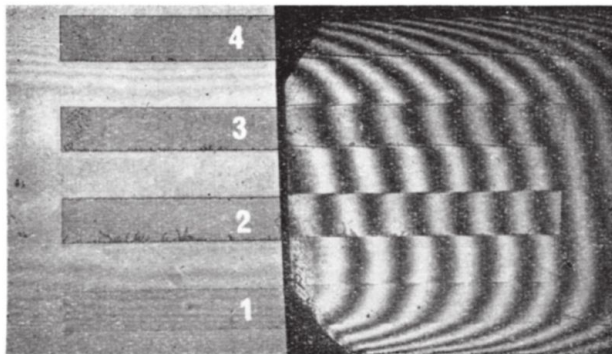


图2c. 双光束单通干涉图（6,328埃），它显示了感光乳胶的收缩程度以及在4种不同曝光量下（比例为 $\times 1$ 、 $\times 2$ 、 $\times 3$ 、 $\times 4$ ）用柯达649F感光乳胶得到的相应的相位变化，并用柯达铬像增强剂作了适当的漂白，以获得残余吸收量最小的近乎纯的“相位物体”。 [英文](#)

相位物体的全息图是用“无透镜傅里叶变换”全息图记录装置记录的，笔者之一^[12,13]首次对这种装置进行了描述，其中，令各个物点发出的球面波与一个“单个”球面参考波相干，而这个参考波来自与物体相邻的平均平面中的“点”源。记录中所用的参考波的半径 $f_1 = 415$ 毫米。（我们可以注意到，在物体与感光乳胶之间不引入任何其他光学元件的情况下，全息图的“无透镜”记录可以对物体的相位分布信息进行存储，这避免了任何程度上的外来散射，而这种散射可能会降低所用方法的保真度和灵敏度。） [英文](#)

图3、图4和图5是通过“无透镜傅里叶变换”全息图得到的重建图像。图3是一个傅里叶变换重建图像，其未经滤波，仅是用单色平面波（6,328埃）透过全息图，并在一个 $f_2 = 600$ 毫米的透镜的焦平面上记录一个边带像而得。与强度或振幅的重建图像不同，图3中相位物体的重

建图像并没有表现出振幅衬度，这是由于物体具有“纯”相位性质。

英文

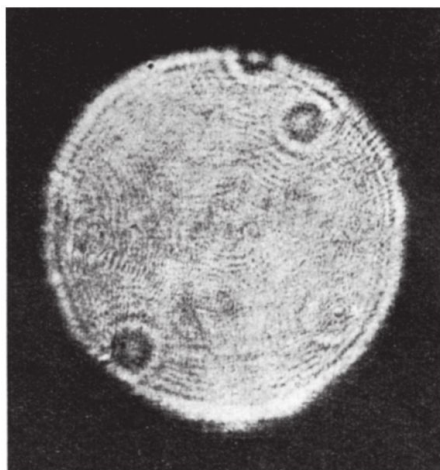


图3．用图1装置中的傅里叶变换重建得到的重建图像，没有做任何相衬增强处理。（根据参考文献12得到了物体的“无透镜”傅里叶变换全息图的记录。）这个像的特征是，在像的相位部分几乎没有任何振幅衬度。（各种各样的干涉效应都是干扰性的，这主要是由于重建光学元件不够干净而造成的。）可以注意到，当原物体是振幅或强度物体^[12,13]而不是纯相位物体时，在相似条件下可以获得极好的像。 英文

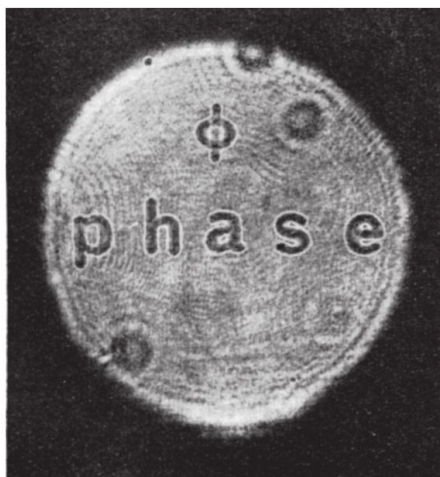


图4a. 通过散焦增强“相衬”得到的相位物体的重建图像（与图1中透镜 L_2 的距离变化为 $-f_2/4$ ，其中 $f_2 = 600$ 毫米）。物体中单词的长度是20毫米（由于放大倍数为 f_2/f_1 ，因此像中长度是30毫米（见图1））。 英文

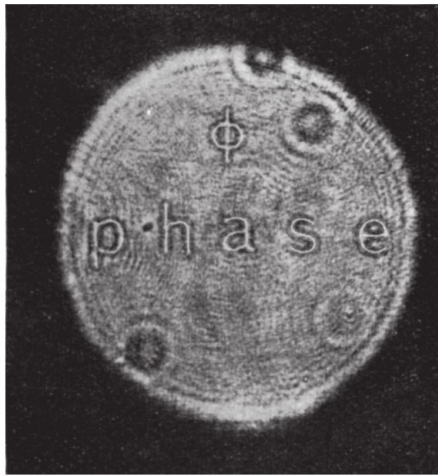


图4b. 利用散焦增强“相衬”得到的相位物体的重建图像（此时散焦，与透镜 L_2 距离变化为 $+f_1/4$ ）。 英文

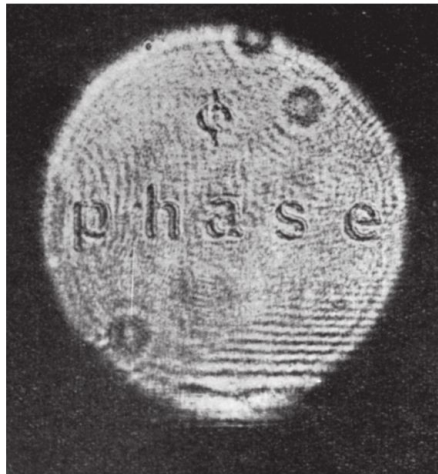


图4c. 在图1的装置中使用相衬滤波器（图2c中所示的其中一个矩形相位条的角）增强相衬而得到的相位物体的重建图像（这里的干涉效应是干扰性的，这是由重建光学器件不够干净造成的）。 英文

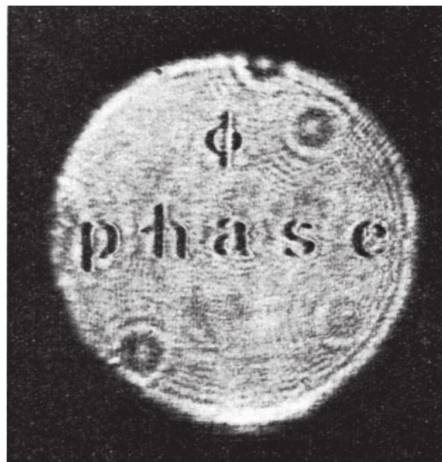


图4d. 在图1的相位滤波板中使用一个傅科刀口边沿增强相衬而得到的相位物体的重建图像。

英文

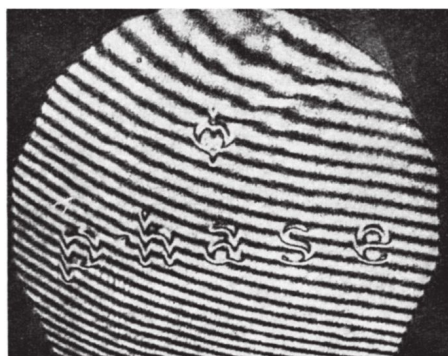


图5. “全息图的全息图”。重建的空间像与平面参考光之间的干涉图样的双光束单通干涉图（激光波长为6,328埃）。将这里所示的像干涉图与通过相似方法得到的图2b中的物体干涉图进行比较，可以证明物体中的相位分布确实得到了保存，并在傅里叶变换波前重建中完全实现了重建。其中使用的是改进型的“相衬”增强装置，如图1所示。（我们可以注意到，相位保存和相位增强重建用作全息图记录时使用的是一个波长，而用于全息图重建时使用的是第二个波长。例如，当 λ_1 属于X射线波段时， λ_2 属于可见光激光波段。）

英文

图4和图5是用人们熟知的相位滤波或相衬法得到的一些衬度很好的相位物体的像，其中相位变化是通过图像中的振幅（即强度）变化来体现的。

英文

图4a和图4b是通过“散焦”相衬增强得到的重建图像，使用的傅里叶变换重建装置与经过严格对焦的图3所用的装置相同，但是相对于图3的准确对焦像，这里都是略微（ $f/24$ 处 $\pm 1/4f_2$ ）偏离焦点对像进行记录的。

英文

图4c是一个准确对焦的像，用图1所示的滤波装置中借助相衬滤波器的角来增强相衬（同样用照片做了记录，并进行了漂白，类似于前文描述的对物体所做的记录）。 英文

图4d是在图1所示的滤波装置中借助傅科刀口滤波器（与单词“phase”垂直）增强“相衬”得到的一个准确对焦的像。 英文

图5是一幅重建空间像的双光束干涉图，它由空间像与一个平面波（通过适当的光束分束装置）的干涉所形成：通过比较相位物体的干涉图（图2b），可以很容易地对相位保持的程度和“相位保持”重建的保真度进行评估。 英文

将图4和图5的像和像的干涉图与图2的相位物体和物体-干涉图对比，可以清晰地看出，记录在全息图内相位物体的相位分布不仅可以获取，而且相位物体中像的相位也能容易地借助于相衬法或其他图像-滤波方法，包括各种类型的干涉测量方法，以重建图像的振幅（各自强度）来表示。我们可能会注意到一些迹象，就是以1/1的参考/衍射场强比（而不是本文中所用的大约5/1的场强比）记录的相位物体的全息图，似乎可简单地在“传统的”傅里叶变换重建装置的焦点处表现出某些明显的“相衬”增强。 英文

我们感谢雷斯特里克提出的建议。本项研究工作部分由美国国家自然科学基金会及美国海军研究办公室支持。 英文

（沈乃澂 翻译；熊秉衡 审稿）

Ball Lightning as an Optical Illusion

E. Argyle

For centuries, eyewitness accounts have attested to an elusive atmospheric phenomenon known as ball lightning: the creation during thunder storms of spherical balls of luminous energy which float through the air, persist for several seconds before abruptly disappearing, and range in size from that of a small stone to several feet in diameter. The phenomenon has been controversial, because it is difficult to study scientifically. Several reported incidents in 1970 here led Edward Argyle to suggest that ball lightning is an optical illusion due to visual afterimages. Argyle's explanation remains one of many possibilities, and controversy over the causes or even the reality of ball lightning continues today. [中文](#)

DURING the past year there have been numerous publications on ball lightning¹⁻⁹, many attempting to account for the formation, properties and behaviour of lightning balls. None have questioned the reality of the phenomenon, in spite of the lack of progress toward an understanding of these baffling objects. Serious doubt about the existence of ball lightning was expressed by Humphreys¹⁰ in 1936, and more recently by Schonland¹¹. Both regarded the phenomenon as probably an optical illusion. Now that Altschuler *et al.*⁸ have invoked nuclear reactions to account for the lightning ball it seems appropriate

to re-examine the possibility of finding an explanation in the physiology of vision. [中文](#)

The phenomenon of visual afterimages is very complex, but is predominant effect—the negative afterimage—is well known. Of less frequent occurrence is the positive afterimage, which results from the observation of a light source which is very bright relative to the surround. In this communication I shall assume that a spherical region of ionized air and white hot particles is sometimes generated at the ground end of a lightning stroke by partial vaporization of Earth, vegetation or metal, and that the luminous intensity within the sphere is high enough to create a positive afterimage in the eye of an observer. In his comprehensive survey of reports on ball lightning Rayle¹² made the interesting discovery that “the number of persons reporting ball lightning observations is 44% of the number reporting observation of ordinary lightning impact points”. This can be understood by assuming that about half of all strokes to ground generate a high luminosity ball at the impact point. Indeed, this sort of assumption is required whether ball lightning is real or illusory.

[中文](#)

The behaviour and apparent properties of the positive afterimage are strikingly similar to those of ball lightning. Its shape will be the same as that of the exciting source, and it will commonly be described as a ball. The apparent size of the positive afterimage will be the same as that of the exciting source only if it is “projected” by the observer to the distance of the source. If the source is outdoors, for example, but the observer focuses on the window through which it was seen, the apparent size will be reduced. Thus the relatively small size of indoor lightning balls is accounted for. Rayle¹² pointed out that linear size and distance were one of the few pairs of parameters that showed a significant correlation, but he did not go on to infer the implied limited range of angular diameters. [中文](#)

The colour of positive afterimages depends more on the brightness of the source than on its colour. There is no conflict with the yellows, oranges and occasional other colours reported for ball lightning. The degree to which the size, shape, brightness and colour of the lightning ball remains constant throughout its lifetime of a few seconds is the despair of both the theoretician^{8,13-16} who seeks a plausible physical mechanism for it, and the experimenter³ who tries to reproduce it. On the other hand, the approximate constancy of these features is characteristic of a positive afterimage. [中文](#)

Being a cone effect, the positive afterimage will usually be formed near the centre of the retina, and the observer, wishing to examine the supposed object, will attempt the impossible task of centring it exactly. The result is a linear drift of the projected positive afterimage across the observer's visual background, as the eye muscles try to correct the centring error. In natural circumstances this feedback motion will be combined with varying amounts of voluntary adjustment as the observer strives to make sense out of the motion.

[中文](#)

Passage through physical surfaces such as a glass or metal screen is possible for positive afterimages and is reported for lightning balls^{3,4}. In neither case is the surface burned or damaged, nor is the size, shape, colour or brightness of the ball altered by the penetration.

[中文](#)

Positive afterimages last 2–10 s, depending on circumstances, and most lightning balls are reported to have a duration in the same range¹². Positive afterimages disappear rather suddenly, as do lightning balls. Positive afterimages generate no sound but the typical observer finds it easy to imagine “suitable” accompanying sounds, if he has any relevant preconceptions. The ease with which most people “hear” appropriate sounds while observing natural phenomena has been documented by Beals¹⁷, who found that most of the inhabitants

of northern Canada claimed to have heard the aurora borealis. The spectrum of sounds reported was persuasively narrow and differed only moderately from observer to observer. Apparently it is no more maladaptive to hear the rustling of the northern lights than it is to hear the implosive pop of a disappearing lightning ball. Curiously, the disappearance of indoor lightning balls is reported often to be violent but seldom to be damaging. 中文

The psychological principle for imagining odour is the same as for sound but fewer individuals have strong odour expectations and in only a few cases are odours reported. An appropriate odour would be one the observer associates with electrical apparatus, if he has some familiarity with it; or with deeper metaphysical concomitants of danger and mystery, such as fire and brimstone, if his associations tend to the supernatural. Such are the reported odours of ball lightning¹⁸. 中文

In bright daylight positive afterimages are a rare occurrence. But in subdued light, as during a thunderstorm, especially if the observer is indoors, a positive afterimage is readily formed by any source as intense as a frosted light bulb. Considering that lightning is primarily an outdoor phenomenon it is remarkable how many lightning balls are seen indoors. This strange fact can be understood if positive afterimages are involved. 中文

That the unsuspecting observer of a chance natural phenomenon can be misled by a positive afterimage is more than speculation. Two of the eyewitnesses to the passage of the Revelstoke bolide¹⁹ reported independently that the meteor had landed on low ground in the middle distance, and had bounced several times before going out. It is more likely that these observers each followed a positive afterimage down to zero elevation after the bolide passed behind distant mountains. At ground level a conflict between positive afterimage drift and physical anticipations led to an unstable situation in which

the positive afterimage oscillated briefly before disappearing. 中文

There are a few reports which indicate the release of large amounts of energy from the lightning ball. In the most famous of these cases, described by Goodlet²⁰, water in a rain barrel was heated by a lightning ball. If ball lightning is an optical illusion it will be necessary to categorize this and similar reports as unreliable. To do so would not be unreasonable in view of the many observations on record. 中文

Final resolution of the question of the nature of ball lightning will no doubt depend more on the outcome of further experimentation than on the collection of more observer reports. Fortunately, the question of the reality of ball lightning is amenable to laboratory investigation. I have found it easy to simulate the lightning ball by using light bulbs, strobe-flash lamps and photographic flash bulbs as intense sources for the generation of drifting positive afterimages. This qualitative work requires verification, however. It is hoped that a laboratory equipped for psychovisual studies will take up the problem and report on the degree to which descriptions of “artificial” ball lightning resemble those of the natural phenomenon that are recorded in the scientific literature. 中文

(230, 179-180; 1971)

Edward Argyle: Dominion Radio Astrophysical Observatory, Penticton, British Columbia.

Received December 7; revised December 20, 1970.

References:

1. Lowke, J. J., Uman, M. A., and Lieberman, R. W., *J. Geophys. Res.*, **74**, 6887 (1969).
2. Jennison, R. C., *Nature*, **224**, 895 (1969).
3. Powell, J. R., and Finklestein, D., *Amer. Sci.*, **58**, 262 (1970).
4. Covington, A. E., *Nature*, **226**, 252 (1970).
5. Bromley, K. A., *Nature*, **226**, 253 (1970).
6. Felsher, M., *Nature*, **227**, 982 (1970).
7. Hill, E. L., *Amer. Sci.*, **58**, 479 (1970).
8. Altschuler, M. D., House, L. L., and Hildner, E., *Nature*, **228**, 545 (1970).

9. Zimmerman, P. D., *Nature*, **228**, 853 (1970).
10. Humphreys, W. J., *Proc. Amer. Phil. Soc.*, **76**, 613 (1936).
11. Schonland, B., *The Flight of Thunderbolts* (Clarendon Press, Oxford, 1964).
12. Rayle, W. D., *NASA Technical Note TN D-3188* (Washington, DC, 1966).
13. Bruce, C. E. R., *Nature*, **202**, 996 (1964).
14. Singer, S., *Nature*, **198**, 745 (1963).
15. Hill, E. L., *J. Geophys. Res.*, **65**, 1947 (1960).
16. Wooding, E. R., *Nature*, **199**, 272 (1963).
17. Beals, C. S., *J. Roy. Astron. Soc. Canad.*, **27**, 184 (1933).
18. Barry, J. D., *J. Atmos. Terr. Phys.*, **29**, 1095 (1967).
19. Folinsbee, R. E., Douglas, J. A. V., and Maxwell, J. A., *Geochim. Cosmochim. Acta*, **31**, 1625 (1967).
20. Goodlet, B. L., *J. Inst. Elec. Eng.*, **81**, 1 (1937).

球状闪电是一种视错觉

阿盖尔

几个世纪以来的目击证据已证明有一种被称为球状闪电的神秘大气现象是存在的：在遭遇雷暴天气时会形成一些漂浮于空气中的具有光能的球状物，短暂停留几秒钟然后突然消失，它们的大小从一块小石头尺寸到几英尺直径不等。因为很难通过科学方式来研究这一现象，所以人们对此一直争论不休。1970年报道的几桩事件使爱德华·阿盖尔联想到球状闪电可能是由视觉余像引起的错觉。阿盖尔的解释只是多种可能性中的一种，人们对球状闪电的成因甚至球状闪电的真实性的争论直到现在也没有停止。 [英文](#)

去年发表的关于球状闪电的文章^[1-9]数不胜数，其中有很多文章在试着解释闪电球的形成过程、属性特征和活动特点。尽管人们在理解这些莫名其妙的现象方面并未取得进展，但却从来没有人质疑过这一现象的真实性。1936年，汉弗莱斯^[10]对球状闪电的存在提出了强烈的质疑，最近舍恩兰德^[11]也表达了同样的观点。他们都认为这一现象可能是一种视错觉。既然阿尔特舒勒等人^[8]都已经引入了核反应来解释这个闪电球，那么人们似乎值得重新审视在视觉生理学中寻找一种解释的可能性。 [英文](#)

虽然视觉余像现象非常复杂，但它最主要的效应——负余像是大家所熟知的。正余像的出现频率略低，它是在我们观察一个比周围环境亮得多的光源时产生的。在这篇文章中，我将要假设大地的水蒸气、植物或金属有时能够被闪电靠地面的一端击中，从而形成了由电离气体以及高温粒子组成的球状区域，并且从这个球内发出的光的强度足够高，以至于能在观察者的眼中形成一个正余像。雷勒^[12]在他的报告中全面考查了有关球状闪电的情况，他发现了一个有趣的现象：“报告观察到球状

闪电的人数是报告看到一般闪电击中某个点的人数的44%”。这一现象可以通过假设有大约半数的击中地面的闪电在击中点处产生了高光度的球来解释。事实上，无论球状闪电是真实的还是虚幻的，这类假设都是必不可少的。[英文](#)

正余像效应的行为和表观特性与球状闪电非常相似。正余像的形状总是和激发源的形状保持一致，人们通常会用一个球来描述正余像的形状。只有在正余像被观察者“投射”到与他和激发源之间的距离一样远时，所看到的正余像才会和激发源的大小相同。举例来说，如果激发源在户外，而观测者把注意力集中在窗户上，通过窗户看外面的激发源，那么他看到的尺寸会小于实际的大小。这样就可以解释在室内观察到的闪电球为什么相对较小了。雷勒^[12]指出线性尺寸和距离是能表现出显著相关性的为数不多的参数中的一对，但是他没有继续提到这意味着角直径存在极限范围。[英文](#)

正余像的颜色主要取决于激发源的亮度，而非激发源的颜色。在关于球状闪电的报告中提到过黄色、橙色，偶尔还出现过其他颜色，这些颜色都是合理的。在几秒钟的生命期内，闪电球的尺寸、形状、亮度以及颜色能在一定程度上保持稳定的现象使想要寻找一个合理的机制来解释球状闪电的理论家^[8,13-16]和想要再现球状闪电现象的实验家^[3]感到无计可施。而另一方面，这些特征的近似稳定不变又恰好是正余像效应所特有的。[英文](#)

正余像属于视椎细胞效应中的一种，它通常会在视网膜中心附近成像，而想要看清这一假想目标的观察者，会试图使其更精确地聚焦在视网膜的中心，尽管这是不可能做到的。如果观察者的眼部肌肉试图校正这一偏离中心的误差，就会导致正余像投影在观察者的视觉背景中产生线性漂移。在自然环境中，当观察者努力弄清这种反馈运动的意义时，反馈运动将会与不同程度的自发调整动作结合在一起。[英文](#)

正余像穿过诸如玻璃屏或金属屏这样的物质表面是有可能的，这已在闪电球的报道中得到了证实^[3,4]。不论在哪种情况下，物质表面都不会被烧焦或破坏，而且余像的尺寸、形状、颜色或亮度也不会因为穿过过程而发生变化。[英文](#)

正余像可以持续2秒~10秒，持续时间长短与周围环境有关，据报道大多数闪电球的持续时间具有同样的量级^[12]。与闪电球一样，正余像的消失会很突然。正余像在产生时是没有声音的，但是假如普通的观察者事先对该现象的产生有所预见，那么他会发现想象出“合适”的伴随音并不是一件很难的事情。比尔斯^[17]已经证明：在观察自然现象时，多数人能轻而易举地“听到”适当的声音，他发现大多数居住在加拿大北部的居民曾声称听到过北极光的声音。报道的声音频谱有很高的吻合度，在不同观察者所描述的声音之间并没有太大的差别。显然，如果能够听到一个正在消失的闪电球发出的爆裂声，那么听到北极光的沙沙声也就是很自然的事了。奇怪的是，报道称人们在室内看到的闪电球在消失时通常是很猛烈的，但是几乎不会造成破坏。 [英文](#)

根据心理学原理，在听觉和嗅觉上的幻觉是一样的，但是很少有人对气味有强烈的预期，因此关于球状闪电有气味的报道只有为数不多的几个例子。一种适当的气味可以让观察者联想到他所熟悉的某种电气设备；或者更玄妙地和危险、神秘联系起来。比如，如果他的联想朝超自然的方向延伸，他会联想到地狱里的磨难。以上谈到的是对球状闪电气味的报道^[18]。 [英文](#)

在白天日光非常强烈的情况下，正余像是十分罕见的。但是，当光线暗淡的时候，比如恰好遇到雷暴天气，尤其是在观察者处于室内的情况下，任何一个亮度类似于磨砂灯泡的光源都很容易使正余像得以形成。因为闪电主要是发生在户外的现象，所以在室内看到那么多闪电球就会显得不同寻常。如果用正余像来解释，这一奇怪现象就不言自明了。 [英文](#)

一个确信自己看到了自然界中偶尔发生的现象的观察者，很有可能是被正余像欺骗了，这一论点绝不仅仅是一个推测。两名看到了雷夫尔斯托克火流星下落的目击者^[19]分别报告称流星落在了不远处的低地上，并且在地面上弹了几下才熄灭。很可能这两位观察者的视线在火流星落到远处的山峰后面之后，就跟随着正余像降到了海拔为零的地方。在地面上，正余像漂移与物理预期之间的偏差导致了一个不稳定的状态，处于这种状态下的正余像在消失之前会发生短暂的振动。 [英文](#)

有几份报告指出，大量的能量会从闪电球中释放出来。最著名的例子要数古德利特^[20]所描述的雨桶中的水被闪电球烧热的现象。如果球状闪电是一种视错觉，那么就应当将这个报告以及一些类似的报告归为不实的报告。这样做并非不讲道理，因为有很多观察记录可以证明这一点。 [英文](#)

毫无疑问，要最终解决球状闪电的本质问题还需要更多的实验结果来验证，而非更大量地收集观察者的报告。幸运的是，通过实验研究就可以揭开球状闪电的真相之谜。我发现很容易用灯泡、频闪闪光灯和摄影闪光灯作为强光源模拟闪电球以产生漂移的正余像。不过，这种定性研究还需要得到进一步的证实。我们希望有一个配备心理视觉研究设备的实验室能够接受这一课题；并且希望在科学文献中对“人造”球状闪电的报道量接近于对自然现象中球状闪电的报道量。 [英文](#)

（孟洁 翻译；肖伟科 审稿）

Synchrotron Radiation as a Source for X-ray Diffraction

G. Rosenbaum *et al.*

The new DESY synchrotron accelerator in Hamburg, Germany, had recently become operational. Here biologist Gerd Rosenbaum of the Max Planck Institute for Medical Research and his colleagues demonstrate the potential usefulness of this accelerator as an intense source of X-rays for imaging in biology. Relativistic electrons travelling around on DESY's circular path naturally emitted X-rays in beams roughly 100 times brighter than any produced by then standard X-ray sources. The researchers show that this source could be used to produce images of biological specimens that are far clearer than those using the best conventional sources. Synchrotron X-ray sources have now become indispensable for imaging in biology. [中文](#)

WHEN an electron is accelerated it emits radiation. At the very high energies used in DESY, the emitted radiation is confined to a narrow cone about the instantaneous direction of motion of the electron. Thus the synchrotron radiates tangentially. Synchrotron radiation is polychromatic, with a peak in the X-ray region for an electron energy of 7.5 GeV (see ref. 1 for the original theoretical description and refs. 2–4 for experimental details). [中文](#)

The DESY synchrotron uses bursts of 50 pulses/s and each 10 ms pulse

contains 6×10^{10} electrons (10 mA average beam current). The injection energy is relatively low and the electrons are accelerated up to 7.5 GeV in the 10 ms. [中文](#)

Most of the X-radiation is emitted during the last 3 ms of each pulse: little radiation is produced at the lower electron energies, and so the time averaged intensity at 1.5 Å is about 20% of the peak value.

[中文](#)

We have evaluated the spectral luminance (that is, the power in photons per second radiated per unit area, solid angle, and wavelength interval) of both the synchrotron and a fine-focus rotating anode X-ray tube (see Table 2). The values are 2×10^{22} (time averaged) and 3×10^{20} photons s^{-1} sterad $^{-1}$ cm $^{-2}$ Å $^{-1}$ respectively at 1.54 Å, showing clearly that the synchrotron is, relative to present X-ray tubes, a very bright source. The actual advantage to be gained in a diffraction experiment depends critically on the optical system necessary to focus and monochromate the radiation. Three types of focusing monochromators used in normal X-ray diffraction can be used: bent glass mirrors, quartz monochromators and graphite monochromators. [中文](#)

A preliminary investigation of the properties of bent quartz monochromators⁵ used with synchrotron radiation is reported here. We have chosen quartz because of its suitable elastic and optical properties which allow it to be used asymmetrically cut and bent to form an accurate focusing monochromator, with a comparatively large numerical aperture. It also behaves substantially as a perfect crystal with a reflectivity near unity in a narrow angular range. We predict that it should be possible to focus the synchrotron radiation down to a point ($200 \times 200 \mu\text{m}^2$) with a Berreman⁶ monochromator to give a total flux of 10^{10} photons s^{-1} at 1.5 Å, which is higher than the flux available from other known X-ray sources (Table 2); also the beam is well collimated. The flux density, the important parameter when using

film, is comparatively even higher because of the small focus.

[中文](#)

Because of its large mosaic spread (300 times greater than that of quartz) a graphite monochromator might seem advantageous for our application. When used with the white radiation from the synchrotron, however, the mosaic spread of graphite would produce a highly divergent reflected beam with considerable wavelength inhomogeneity, thus restricting us to small monochromator-film distances for reasonable spot diameters on the film. For these short distances it would not then be possible to collect radiation from a large area of graphite by focusing. Alternatively, for larger film distances the reflected beam would require collimation, which would again reduce the expected intensity. We do not, therefore, expect graphite to give more intensity than quartz. Furthermore, the optical and mechanical properties of graphite are much less convenient.

[中文](#)

Experimental Details

All experiments took place in the F41 (synchrotron radiation) group bunker at DESY in Hamburg (Fig. 1 and 2). The experimental area can only be entered when the main beam shutter between the synchrotron and the bunker is closed so that all the experiments had to be done by remote control. The quartz crystal was mounted in the vacuum pipe leading to the synchrotron ring. The reflected beam came out through a beryllium window (0.5 mm thick) of diameter 1.5 cm. A rotating disk containing a slot was used as an attenuator. This and a lead shutter were mounted near the window. The rotating disk was arranged to run synchronously with the synchrotron. A film holder was mounted about 120 cm from the quartz crystal on a table movable by remote control. Intensities were recorded on Ilford Industrial G film. The monochromator (Steeg and Reuter) consisted of a slab of quartz ($45 \times 13 \times 0.3$ mm³) with the face containing the long axis cut at about 8° to the 1011 planes. The slab was bent by two sets of pins.

Before mounting the crystal in the beam, the curvature was pre-adjusted to the required radius with laser light. The final position of the focus was determined by through-focal photographs. The best focal line had a width of $180\text{ }\mu\text{m}$ and represented the image of the radiating electron beam in the synchrotron. (The total effective source size, including the betatron and synchrotron oscillations, was about 4 mm.) Photographs were also taken close to the monochromator, where the reflected beam was wide, to evaluate the total reflected flux. Experiments with aluminium filters were made to estimate the strength of the higher harmonics in the quartz reflected radiation.

中文

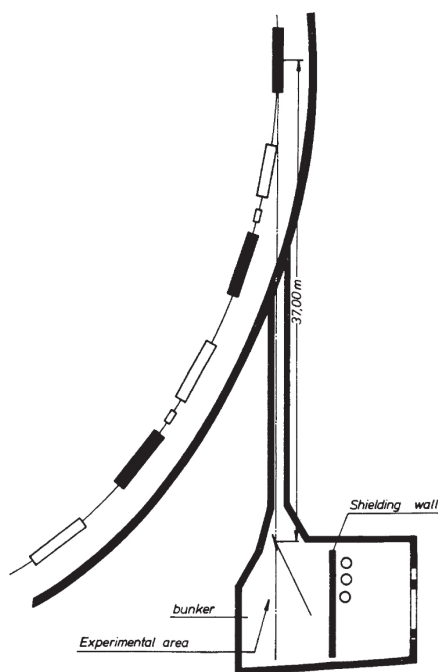


Fig. 1. The F41 bunker at DESY and its position with respect to the synchrotron.

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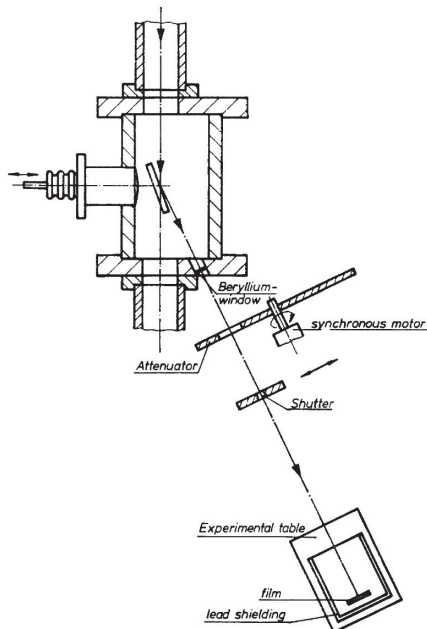


Fig. 2. Monochromator housing and the experimental set-up.

中文

With a source-to-monochromator distance of about 40 m the crystal, if set exactly for one wavelength (for example, in the Johann arrangement⁵), would give a focus at 10 m. The white radiation fortunately allowed us to relax this condition and obtain a more practical focal length (1.5 m) at the expense only of very little wavelength inhomogeneity (Table 1). Furthermore, the angular adjustment of the quartz monochromator was not critical. The central wavelength of the reflected beam was determined by measuring the angle between incident and reflected beam. The position and size of the Be-window limited our observations to Bragg angles of $13 \pm 1^\circ$ (that is, $1.5 \pm 0.15 \text{ \AA}$). 中文

Finally, a simple camera was constructed (specimen-film distance 40 cm), and a photograph (Fig. 3a) was taken of the equatorial reflexions from a 2 mm strip of the longitudinal flight muscle from the giant water bug *Lethocerus maximus*⁷. The entrance aperture of the camera was approximately $2 \text{ mm} \times 2 \text{ mm}$. A helium-filled tube minimized air absorption in the space between the radiation-pipe window and the

camera. The exposure was 15 min with the synchrotron running at 5 GeV. On one side of the direct beam a large area of parasitic scattering is visible apparently resulting from the quartz and from the steel pins used to bend the quartz. Fortunately, the camera entrance-slits were not symmetrically positioned, so that a clear view of one side of the diffraction pattern was obtained. The substantially greater width of the “20” line on the photograph made with synchrotron radiation, compared with that made using a conventional X-ray source (Fig. 3b, Elliott fine-focus rotating anode tube and bent quartz monochromator) has not been explained. The comparative intensity of the two photos shows that the synchrotron (at 5 GeV) is about ten times more effective than one of the most intense X-ray sources currently available. 中文

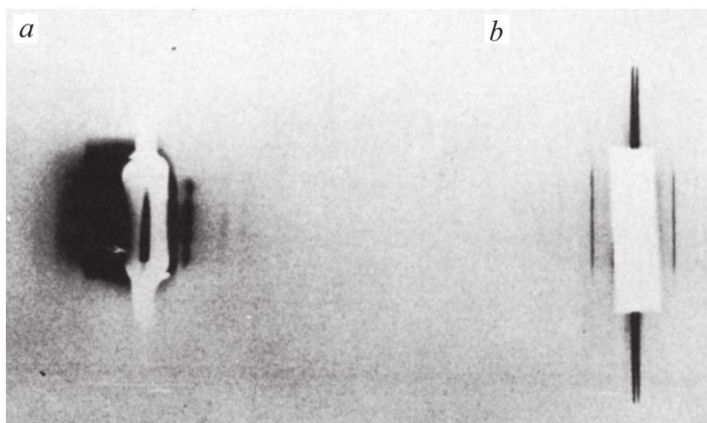


Fig. 3. Equatorial reflexions from dorsolongitudinal flight muscle of *Lethocerus maximus* recorded with: *a*, monochromated synchrotron radiation; electron energy 5 GeV, beam current 8 mA, exposure time 15 min, specimen film distance 40 cm; note the parasitic scattering on the left of the backstop arising from fluorescence from the monochromator holder; *b*, Elliott fine-focus rotating anode tube at 40 kV, 15 mA, exposure time 1 h, specimen film distance 36 cm. The strong line is the 20 reflexion ($d = 231 \text{ \AA}$); the weak lines are the 21, 31 and 32 reflexions. 中文

Calculated and Observed Intensities

Using the theory of Schwinger¹ and a programme written by Klucker, DESY group F41, we have calculated the intensities at $1.5 \text{ \AA}$

wavelength and at the harmonics of 1.5 Å:when the synchrotron runs at 7.5 GeV the second and third harmonics are twice as intense (photons/s) as the 1.5 Å radiation.

中文

We have measured photographically the instantaneous intensity of the reflected beam passing the disk attenuator at the eighth ms of each synchrotron acceleration cycle. The contribution of higher orders has been estimated from measurements made through aluminium filters of various known thicknesses, and we have adopted values for the absorption coefficients⁸. The sensitivity of Ilford Industrial G film at 1.5 Å has been extrapolated from the calibrated value at 1.54 Å (ref. 9). The experimental conditions and data are summarized in Table 1.

中文

Table 1. Data for Quartz Monochromator in Synchrotron Radiation Beam

Synchrotron	7.5 GeV, 10 mA beam current
Electron beam diameter	approximately 4 mm (=effective X-ray source diameter)
Distance	37 m from synchrotron to monochromator
Cross-fire of the incident beam	approximately 10 ⁻⁴ rad
Polarization	85% at 1.5 Å in the eighth ms of the cycle, polarized in the plane of the synchrotron
Be-window	0.5 mm (96 mg cm ⁻²)
Crystal	quartz cut at σ=8°30' to the 1011 planes, dimensions 45×13×0.3 mm ³
Bender	pins: outer pair 40.5 mm inner pair 39.5 mm radius of curvature of crystal, 9 m
Wavelength	1.53 Å (θ = 13°15')
Wavelength spread	Δλ = 3×10 ⁻³ Å (due to deviation from Johann focusing and to finite source size)
Focus	1.5 m from crystal, line focus 180 μm wide
Angular aperture of reflected beam	horizontal: 2 mrad (convergence) vertical: 3–4 mrad (divergence)
Measured flux in line focus	1.8×10 ⁹ photons s ⁻¹ mm ⁻¹ (of focal length) (at the eighth ms of the cycle)

中文

The ratio of the intensity at 1.5 Å, evaluated as indicated above, to the calculated incident intensity per unit wavelength interval is an “integrated band pass” which was found to be

$$\int R(\lambda)d\lambda = 0.7 \times 10^{-4} \text{ Å}$$

Transforming the wavelength into an angle using Bragg’s law we find an integrated reflectivity

$$\int R(\theta)d\theta = R_{\text{int}} = 1.0 \times 10^{-5} \text{ rad}$$

for a quartz crystal cut at $8^\circ 30'$ to the $10\bar{1}1$ plane. [中文](#)

Quartz behaves essentially as a perfect dynamical diffractor¹⁰. Renninger¹¹ has calculated the reflectivity of a perfect quartz crystal (without corrections for absorption) to be

$$R_{\text{int}} = 4.4 \times 10^{-5} \text{ rad}$$

and Brogren¹² measured an integrated reflectivity of

$$R_{\text{int}} = 3.9 \times 10^{-5} \text{ rad}$$

for a polished quartz crystal cut parallel to the $10\bar{1}1$ planes. The case of an asymmetrically cut perfect crystal with absorption is treated in the Darwin–Prins theory. Using Zachariasen's formulae¹³ we have calculated an integrated reflectivity of

$$R_{\text{int}} = 1.45 \times 10^{-5} \text{ rad}$$

for a quartz crystal cut at $8^\circ 30'$ to the $10\bar{1}1$ planes ($\lambda = 1.5 \text{ \AA}$) which agrees with our experimental value. [中文](#)

We emphasize that the aim of our experiments was not to make quantitative measurements of the reflectivity of quartz but to show that quartz is a suitable material for the construction of a focusing monochromator for synchrotron radiation, and to check that there was no large disparity between the observed and calculated flux of monochromated synchrotron radiation. Our results show that the monochromator has properties which can be accurately predicted. We have emphasized neither the accurate determination of the attenuation ratio of the rotating disk nor the speed of the shutter. Moreover, the evaluation of the contribution from higher harmonics may be inaccurate. We estimate that the error in our result may amount to 50%. Furthermore, the state of the surface of the quartz

crystal is difficult to control, although it has a considerable influence on the actual shape and height of the reflectivity curve^{14,15}. 中文

Estimated Intensities for Various Configurations

We intend to set up a Berreman monochromator⁶ to give a point-focused beam from a quartz crystal ground so as to give the required curvature in one plane and bent to the corresponding curvature in the second. There seem to be no theoretical reasons why this should not produce foci of similar dimensions to those that we have obtained with a simple bent crystal, especially as the geometry of the synchrotron beam relaxes some of the stringent conditions which the radii of curvature of the crystal must otherwise satisfy. 中文

The estimated performance of such an arrangement for each of three typical configurations used in biological applications of X-ray diffraction is shown in Table 2, and the performance is compared with a “conventional” fine-focus rotating anode tube. The calculated intensities are based on the effective band pass give above, 0.7×10^{-4} Å. 中文

Table 2. Biological Applications

Specimen	Elliott fine-focus X-ray tube*	DESY synchrotron with Berreman point-focusing monochromator‡
Single crystal <i>a</i> = 0.5 mm <i>b</i> = 0.5 mm <i>L</i> = 7.5 cm	Standard collimator, 0.5 mm diameter <i>A</i> = 12.5 cm <i>d</i> = 0.7 mm <i>P</i> = 10^9 photons s ⁻¹ <i>I</i> = 2×10^9 photons s ⁻¹ mm ⁻²	<i>D</i> = 1 m <i>d</i> = 120 μm <i>P</i> = 4×10^9 photons s ⁻¹ <i>I</i> = 2.5×10^{11} photons s ⁻¹ mm ⁻²
Tobacco mosaic virus gel <i>a</i> = 0.6 mm <i>b</i> = 1 mm <i>L</i> = 12 cm	Double-crystal focusing monochromator† <i>d</i> = 80 μm <i>P</i> = 10^7 photons s ⁻¹ <i>I</i> = 2×10^9 photons s ⁻¹ mm ⁻²	<i>D</i> = 0.8 m <i>d</i> = 100 μm <i>P</i> = 3×10^9 photons s ⁻¹ <i>I</i> = 3×10^{11} photons s ⁻¹ mm ⁻²
Insect muscle <i>a</i> = 3 mm <i>b</i> = 0.3 mm <i>L</i> = 40 cm	Double-crystal focusing monochromator† <i>d</i> = 100 μm <i>P</i> = 5×10^9 photons s ⁻¹ <i>I</i> = 5×10^7 photons s ⁻¹ mm ⁻²	<i>D</i> = 1.5 (3) m <i>d</i> = 180 (350) μm <i>P</i> = 5×10^9 (2×10^9) photons s ⁻¹ <i>I</i> = 1.5×10^{10} photons s ⁻¹ mm ⁻²

a, Width of specimen; *b*, height of specimen; *L*, specimen film distance; *A*, anode specimen distance; *D*, focal length, that is, monochromator film distance; *d*, spot or focus diameter on

film; P , X-ray power reaching the specimen; and I , flux density at the focus.

* Loaded with 40 kV, 50 mA into a $0.2 \times 2 \text{ mm}^2$ electron focus at the anode in the first case, and 40 kV, 15 mA into a $0.14 \times 0.7 \text{ mm}^2$ focus in the other two cases. This set is the most powerful fine-focus X-ray tube currently available.

† The setting of this Johann-type⁵ monochromator is optimized for each type of specimen.

‡ Conditions of the synchrotron are as in Table 1, computed for $1.5 \text{ \AA}$ radiation. [中文](#)

The tube values were calculated from measurements made with Ilford Industrial G film and a rotating disk attenuator on an Elliot fine-focus rotating anode tube used with single and double focusing quartz monochromators. [中文](#)

Higher Intensities and Longer Wavelengths

Some possible methods of obtaining higher intensities and utilizing the continuous spectrum are as follows. (a) According to current plans, the DESY synchrotron current will be raised from 10 mA to 50 mA. Also the electrons will be kept at the maximum energy for 1 or 2 ms, giving overall a six-fold improvement. (b) Sakisaka¹⁴ suggests that both the height and width of the rocking curve of quartz can be increased appreciably by gentle grinding. A gain of 2 or 3 should be possible without affecting the size of the focus. (c) For special applications, where only pulses of X-rays can be used, the synchrotron is a very advantageous source if the experiment can be synchronized with the periodic maximum emission from the synchrotron. The integrated reflectivity of quartz increases approximately linearly with wavelength up to $3\text{--}4 \text{ \AA}$ (ref. 12). The intensity of the synchrotron radiation decreases, however, in the wavelength range $1.5\text{--}4.5 \text{ \AA}$, approximately as the inverse of wavelength. The reflected intensity is thus roughly independent of wavelength. Previously, long wavelength experiments were avoided because of the low conversion efficiency of the anode materials involved. [中文](#)

We thank the Direktorium of DESY for facilities; Dr. R. Haensel and group F41 for advice; Drs. U. W. Arndt and H. G. Mannherz (who

prepared the muscle specimen) and Dr. J. Barrington Leigh for the use of his calculations for the Berreman monochromator. The equipment was constructed in the workshops of DESY and the Max-Planck-Institut, Heidelberg. G. R. and J. W. have EMBO short term fellowships. 中文

(230, 434-437; 1971)

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Received March 3, 1971.

References:

1. Schwinger, J., *Phys. Rev.*, **12**, 1912 (1949).
2. Godwin, R. P., *Springer Tracts in Modern Phys.* (edit. by Höhler, G.), **51**, 1 (1969).
3. Haensel, R., and Kunz, C., *Z. Angew. Phys.*, **23**, 276 (1967).
4. Bathow, G., Freytag, E., and Haensel, R., *J. Appl. Phys.*, **37**, 3449 (1966).
5. Witz, J., *Acta Cryst.*, **A25**, 30 (1969).
6. Berreman, D. W., *Rev. Sci. Instr.*, **26**, 1048 (1955).
7. Pringle, J. W. S., *Prog. Biophys. Mol. Biol.*, **17**, 3 (edit. by Huxley, H. E., and Butler, J. A. V.) (Pergamon, Oxford, 1967).
8. *International Tables of Crystallography*, 3.
9. Morimoto, H., and Uyeda, R., *Acta Cryst.*, **16**, 1107 (1963).
10. Bearden, J. A., Marzolf, J. G., and Thomsen, J. S., *Acta Cryst.*, **A24**, 295 (1968).
11. Renninger, M., *Z. Kristallograph.*, **107**, 464 (1956).
12. Brogren, G., *Arkiv. för Fysik.*, **22**, 267 (1962).
13. Zachariasen, W. H., *Theory of X-ray Diffraction in Crystals* (Dover, New York, 1967).
14. Sakisaka, Y., *Proc. Math. Phys. Soc. Japan*, **12**, 189 (1930).
15. Evans, R. C., Hirsch, P. B., and Kellar, J. N., *Acta Cryst.*, **1**, 124 (1948); Gay, P., Hirsch, P. B., and Kellar, J. N., *Acta Cryst.*, **5**, 7 (1952).

作为X射线衍射光源的同步辐射

罗森鲍姆等

德国汉堡的新DESY (Deutsches Elektronen Synchrotron: 德国电子同步加速器) 最近开始运行。在本文中, 马克斯·普朗克医学研究所的生物学家格尔德·罗森鲍姆及其同事们证明了这台加速器作为强X射线源在生物成像方面的潜在用途。在DESY环路中运动的相对论性电子自然发射的X射线束要比当时的标准X射线源所产生的射线束亮100倍左右。研究人员发现: 使用这个源产生的生物样品的像比使用最好的传统X射线源要清晰得多。现在, 同步加速器X射线源已经成为不可或缺的生物成像设备。 [英文](#)

当一个电子被加速时, 它会发出辐射。在DESY所用的非常高的能量下, 发出的辐射被限于电子瞬时运动方向周围的窄椎体之内。因此同步辐射是沿切线方向发出的。同步辐射是多波长的辐射, 对于能量为7.5GeV的电子, 其同步辐射的峰值落在X射线范围内 (见参考文献1中对原始理论的描述及参考文献2~4中对实验细节的介绍)。 [英文](#)

DESY同步加速器采用每秒50个脉冲的爆丛, 每10ms脉冲含有 6×10^{10} 个电子 (平均束流为10 mA)。注入能量相对较低, 电子在10ms内被加速到7.5 GeV。 [英文](#)

大多数X辐射是在每个脉冲的最后3ms内发射的: 极少量的辐射来自较低电子能量, 所以在1.5 Å处的时间平均强度约为峰值的20%。
[英文](#)

我们已经估算出同步加速器和细焦旋转阳极X射线管的谱线亮度 (即以单位面积、单位立体角和单位波长间隔内每秒发射的光子数表示的功率) (见表2), 在1.54 Å处分别为 2×10^{22} (时间平均) 个和

3×10^{20} 个光子 $\text{s}^{-1} \text{ sterad}^{-1} \text{ cm}^{-2} \text{ \AA}^{-1}$ 。这清楚地表明：与目前的X射线管相比，同步加速器是一种亮度非常高的源。衍射实验能从中得到多大的实际好处在很大程度上取决于使辐射聚焦和单色化所必需的光学系统。在标准X射线衍射中可以应用三种类型的聚焦单色器：弯曲玻璃镜、石英单色器和石墨单色器。 [英文](#)

本文报道了对用于同步辐射的弯曲石英单色器^[5]性质进行的初步研究。我们选择石英是因为它具有合适的弹性和光学性质，因而可以对它进行非对称切割，并能使之弯曲形成一个具有相当大数值孔径的准确聚焦单色器。实质上它还是一个在窄角度范围内折射率接近于1的理想晶体。我们预言使用贝雷曼^[6]单色器应该可以将同步辐射聚焦到一个点（ $200 \times 200 \mu\text{m}^2$ ）上，在 $1.5 \text{ \AA}$ 处给出的总通量为每秒 10^{10} 个光子，高于从其他已知X射线源得到的通量（表2）；束的准直也很好。因为焦距小，所以通量密度，这个在使用胶片进行测量时的一个重要参数，比起其他X射线源还会更高一些。 [英文](#)

由于石墨有很大的嵌镶度（是石英的300倍），因而石墨单色器或许会有利于我们的应用。然而，当我们使用来自同步加速器的白辐射时，石墨的嵌镶度将导致产生波长相当不均匀的高度发散反射束，因此为了在胶片上形成一个大小合适的光斑，单色器-胶片的距离必须非常短。对于这么短的距离，通过聚焦来收集来自大面积石墨的辐射是不可能的。另一方面，在单色器-胶片距离较大的情况下，反射束需要准直，这也将降低强度的预期值。因此，我们不认为石墨能给出比石英更高的强度。此外，石墨的光学和力学性质在使用上也很不方便。 [英文](#)

实验的详细过程

全部实验都是在汉堡DESY的F41（同步辐射）小组的掩体中进行的（图1和图2）。只有当同步加速器和掩体之间的主射束光闸关闭的时候，人才能进入实验区，所以整个实验必须通过遥控进行。石英晶体被放在通向同步加速器环的真空管内。反射束从一个直径为 1.5 cm 的镀窗（厚 0.5 mm ）中射出。用一个带有狭缝的旋转圆盘作为衰减器。这个衰减器和一个铅闸装在镀窗附近。使旋转圆盘与同步加速器同步运转。胶

片的支架装在一张能通过遥控移动的实验台上，支架距石英晶体约120 cm。在伊尔福工业G胶片上记录强度。单色器（施特格和罗伊特）是由一个石英片（ $45 \times 13 \times 0.3 \text{ mm}^3$ ）构成的，其包含长轴的面的切割角度为相对1011面约成 8° 夹角。石英片的弯曲是通过两组销子实现的。在把晶体安装到光束中之前，先要用激光将曲率半径调整至所需的数值。用经过聚焦的照片确定焦点的最终位置。最佳聚焦线的宽度为 $180 \mu\text{m}$ ，这代表了同步加速器内辐射电子束的像。（包括电子回旋加速器和同步加速器振荡在内的总有效源尺寸约为4mm。）照相也是在靠近单色器处进行的，在这里反射束很宽，便于估计总的反射通量。用铝滤波器所作的实验来估计在石英反射的辐射中高次谐波的强度。 英文

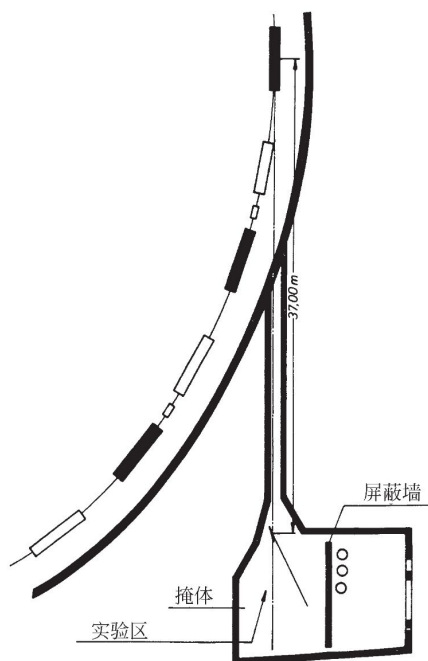


图1 . DESY中的F41靶体及其相对于同步加速器的位置

英文

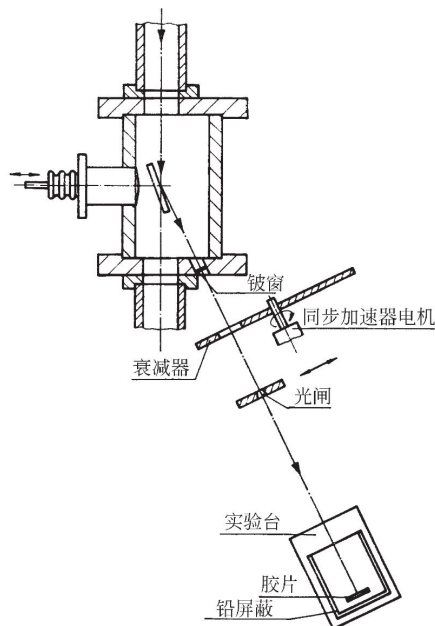


图2．单色器的构造和实验装置 英文

如果源到单色器的距离约为40 m，并且晶体对一个波长精确地设定（例如在约翰式聚焦系统中^[5]），那么给出的焦点将在10m处。所幸的是，白辐射使我们可以放宽这个条件，从而在波长不均匀性损失很小的情况下得到一个更实际的焦距（1.5m）（表1）。此外，对石英单色器的角度调整并不是很重要。反射束的中心波长是通过测量入射束与反射束之间的夹角来确定的。铍窗的位置和尺寸把我们的观测范围限制在布拉格角为 $13^\circ \pm 1^\circ$ 之内（即 $1.5 \text{ \AA} \pm 0.15 \text{ \AA}$ ）。 英文

最后要构造的是一台简易的照相机（样品-胶片的距离为40cm），拍摄的照片（图3a）为巨型水虫纵向飞行肌的一条2mm带状区域^[7]的赤道反射。照相机的进口孔径约为2mm×2mm。用一只充有氦气的管使辐射-管窗与照相机之间的空间内空气吸收最小。在5 GeV运行的同步加速器的曝光时间为15 min。在直射光束的一侧，明显可以看到由石英和用于使石英弯曲的钢质定位销造成的大面积寄生散射。所幸的是，照相机的进口狭缝并不是对称定位的，因此可获得一侧衍射条纹的清晰图像。与采用传统X射线源（图3b，埃利奥特细焦旋转阳极管和弯曲石英单色器）相比，用同步辐射制成的照片具有相对较大的“20”线宽度，这一现象目前尚未得到解释。从两张照片的相对强度可以看出，同步辐射

(5GeV) 比现有的最强X射线源要有效约10倍。 [英文](#)

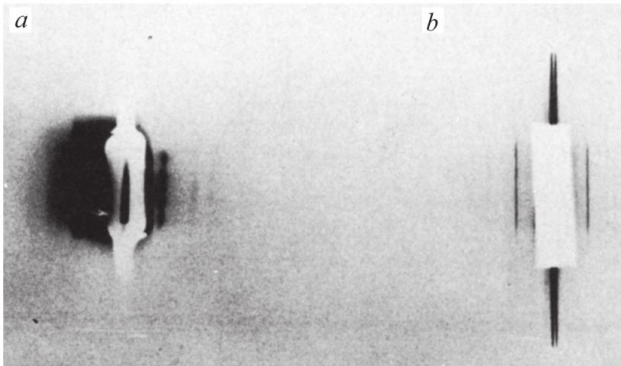


图3．拍摄巨型水虫背部纵向飞行肌的赤道反射，采用以下两种方式记录。*a*，单色的同步辐射；电子能量：5 GeV，束流：8 mA，曝光时间：15 min，样品与胶片的距离：40 cm；注意在托架左侧会出现由单色器支架的荧光引起的寄生散射。*b*，40 kV和15 mA的埃利奥特特细焦旋转阳极管，曝光时间：1 h，样品与胶片的距离：36 cm。强线是20反射（ $d=231\text{ \AA}$ ）；弱线是21、31和32反射。 [英文](#)

计算强度和观测强度

根据施温格^[1]的理论和由DESY的F41小组成员克卢克编写的程序，我们计算了1.5 Å波长处和1.5 Å谐波处的强度：当同步加速器在7.5 GeV运行时，二次和三次谐波的强度（每秒的光子数）是1.5 Å辐射的两倍。

[英文](#)

我们用照相方法测量了在每个同步加速器加速周期第8个ms时通过圆盘衰减器的反射束的瞬时强度。从对不同已知厚度的铝滤波器所作的测量中估计出了高阶的贡献，我们还用到了一些吸收系数数据^[8]。伊尔福工业G胶片在1.5Å处的灵敏度是由在1.54 Å处的校准值外推得到的（参考文献9）。实验条件和数据汇总在表1中。 [英文](#)

表1. 同步辐射束中石英单色器的数据

同步加速器	7.5 GeV, 10 mA 束流
电子束直径	约 4 mm (= 有效X射线源直径)
距离	同步加速器距单色器 37 m
入射束的交叉发射	约 10^{-4} 弧度 (rad)
偏振	对于在同步加速器平面内的偏振：在周期的第8个 ms 内 $1.5 \text{ \AA}$ 处为 85%
铍窗	0.5 mm ($96 \text{ mg} \cdot \text{cm}^{-2}$)
晶体	石英切割到相对1011面为 $\sigma=8^{\circ}30'$ 的夹角，尺寸为 $45 \times 13 \times 0.3 \text{ mm}^3$
弯曲装置	定位销：外对 40.5 mm 内对 39.5 mm 晶体的曲率半径为 9 m
波长	$1.53 \text{ \AA}$ ($\theta = 13^{\circ}15'$)
波长展开度	$\Delta\lambda = 3 \times 10^{-3} \text{ \AA}$ (源自约翰式聚焦的偏差以及有限源的尺寸)
焦点	距晶体 1.5 m，线聚焦的宽度为 $180 \text{ }\mu\text{m}$
反射束的孔径张角	水平：2 mrad (会聚) 垂直：3 mrad~4 mrad (发散)
在线聚焦时测量的通量	(焦距处) 1.8×10^9 个光子 $\text{s}^{-1} \text{ mm}^{-1}$ (在周期的第8个ms内)

英文

由上述方法估计得到的在 $1.5 \text{ \AA}$ 处的强度与单位波长间隔入射强度的计算值之比是一个“积分带通”，可由下式表示：

$$\int R(\lambda)d\lambda = 0.7 \times 10^{-4} \text{ \AA}$$

用布拉格定律将波长转换为角度，我们得到了以相对1011面 $8^{\circ}30'$ 夹角切割的石英晶体的积分反射率：

$$\int R(\theta)d\theta = R_{\text{int}} = 1.0 \times 10^{-5} \text{ rad}$$

英文

石英在本质上是理想的动态衍射器^[10]。伦宁格^[11]已经计算出了一个理想石英晶体的反射率（未作吸收校正）：

$$R_{\text{int}} = 4.4 \times 10^{-5} \text{ rad}$$

布罗格伦^[12]通过测量得到了一个经平行于 $10\bar{1}1$ 面切割的抛光石英晶体的积分反射率：

$$R_{\text{int}} = 3.9 \times 10^{-5} \text{ rad}$$

这类具有吸收的非对称切割理想晶体的情况按照达尔文-普林斯理论来处理。利用扎卡里亚森公式^[13]，我们计算了以相对 $10\bar{1}1$ 面 $8^{\circ}30'$ 夹角切割的石英晶体的积分反射率（ $\lambda = 1.5 \text{ \AA}$ ）：

$$R_{\text{int}} = 1.45 \times 10^{-5} \text{ rad}$$

这与我们通过实验得到的数值是一致的。 [英文](#)

需要强调的是：我们的实验目的并不是定量测量石英的反射率，而是要说明就构成应用于同步辐射中的聚焦单色器而言，石英是一种很合适的材料，并证实了单色同步辐射的观测通量与计算通量之间并无很大的差异。我们得到的结果表明，单色器的性质是可以准确预言出来的。我们既没有强调对旋转圆盘衰减比的准确测定，也没有强调对光闸速率的准确测定。此外，对高次谐波贡献的估计也可能是不准确的。我们估计，在我们所得结果中的误差也许会达到50%。此外，虽然石英晶体的表面状态对反射率曲线的实际形状和高度影响很大^[14,15]，但很难对它进行控制。 [英文](#)

对三类样品的强度估计

为了从石英晶体底部给出一束点聚焦辐射，我们打算装配一台贝雷曼单色器^[6]，以便在一个平面上形成所需的曲率，并在第二个平面上也弯曲到相应的曲率。似乎无法用理论来说明为什么这样做得到的焦距不能与用简单弯曲晶体得到的焦距有类似的大小，尤其是在同步加速器束流的几何形状不那么严格时，晶体的曲率半径本应该满足的这时不满足了。 [英文](#)

以这样一种方式用X射线衍射研究生物学中的三种典型样品，将估测的性能列于表2，并把DESY的性能与“传统的”细焦旋转阳极管的性能进行了比较。强度的计算值是以前面给出的有效带通值 $0.7 \times 10^{-4} \text{ \AA}$ 为基础的。 [英文](#)

表2. 在生物学中的应用

样品	埃利奥特细焦X射线管*	配备贝雷曼点聚焦单色仪的DESY同步加速器‡
单晶 $a = 0.5\text{ mm}$ $b = 0.5\text{ mm}$ $L = 7.5\text{ cm}$	标准准直仪，直径为 0.5 mm $A = 12.5\text{ cm}$ $d = 0.7\text{ mm}$ $P = 10^9\text{ 光子 s}^{-1}$ $I = 2 \times 10^9\text{ 光子 s}^{-1}\text{ mm}^{-2}$	 $D = 1\text{ m}$ $d = 120\text{ }\mu\text{m}$ $P = 4 \times 10^9\text{ 光子 s}^{-1}$ $I = 2.5 \times 10^{11}\text{ 光子 s}^{-1}\text{ mm}^{-2}$
烟草花叶病毒凝胶体 $a = 0.6\text{ mm}$ $b = 1\text{ mm}$ $L = 12\text{ cm}$	双晶聚焦单色器† $d = 80\text{ }\mu\text{m}$ $P = 10^7\text{ 光子 s}^{-1}$ $I = 2 \times 10^9\text{ 光子 s}^{-1}\text{ mm}^{-2}$	 $D = 0.8\text{ m}$ $d = 100\text{ }\mu\text{m}$ $P = 3 \times 10^9\text{ 光子 s}^{-1}$ $I = 3 \times 10^{11}\text{ 光子 s}^{-1}\text{ mm}^{-2}$
昆虫的肌肉 $a = 3\text{ mm}$ $b = 0.3\text{ mm}$ $L = 40\text{ cm}$	双晶聚焦单色器† $d = 100\text{ }\mu\text{m}$ $P = 5 \times 10^5\text{ 光子 s}^{-1}$ $I = 5 \times 10^7\text{ 光子 s}^{-1}\text{ mm}^{-2}$	 $D = 1.5\text{ (3) m}$ $d = 180\text{ (350) }\mu\text{m}$ $P = 5 \times 10^8\text{ (2} \times 10^9\text{) 光子 s}^{-1}$ $I = 1.5 \times 10^{10}\text{ 光子 s}^{-1}\text{ mm}^{-2}$

a ，样品宽度； b ，样品高度； L ，样品与胶片的距离； A ，阳极与样品的距离； D ，焦距，即单色器与胶片的距离； d ，在胶片上的光斑或焦点直径； P ，到达样品上的X射线功率； I ，焦点处的通量密度。

* 对于第一个样品，将40 kV和50 mA加载到阳极处 $0.2 \times 2\text{ mm}^2$ 电子焦点上；对于另外两个样品，将40 kV和15 mA加载到 $0.14 \times 0.7\text{ mm}^2$ 焦点上。这个装置是目前可用的最有效的细焦X射线管。

† 这种约翰式^[5]单色器装置对每一种类型的样品都是最佳的。

‡ 同步加速器的条件如表1所列，以1.5 Å的辐射进行计算。 [英文](#)

X射线管的数据是根据测量伊尔福工业G胶片和与单、双聚焦石英单色器协同使用的埃利奥特细焦旋转阳极管上的旋转圆盘衰减器所得到的结果计算出来的。 [英文](#)

更高的强度和更长的波长

几个可能获得更高强度及连续光谱的方法是：（ a ）按照目前的设计，可以将DESY同步加速器的电流从10 mA升至50 mA。电子也将在1ms~2ms内保持在最大能量，这样一来总强度可以提高至6倍。（ b ）[匈坂^{\[14\]}](#)提出，轻微的抛光可以使石英摇摆曲线的高度和宽度显著增加。在不影响聚焦尺寸的前提下，达到2倍或3倍的增益是有可能的。（ c ）对于一些只能应用X射线脉冲的特殊情况，如果实验能与来自同步加速器的周期性最大辐射同步，那么同步加速器就是一个具有明显优势的源。石英的积分反射率基本上随波长呈线性递增，直到波长达到3 Å~4 Å时（参考文献12）。然而，在波长范围为1.5 Å~4.5 Å时，同步辐射的强度却随波长的增加而下降，两者近似成反比。所以反射强度大

致与波长无关。以前大家都会避免在长波下作实验，因为阳极材料在长波下的转换效率很低。 [英文](#)

感谢DESY委员会为我们提供设备；感谢亨泽尔博士和F41小组所提的建议；感谢阿恩特博士和曼赫茨博士（肌肉样品是他们制备的），以及巴林顿·利博士对贝雷曼单色器的计算。这台设备安置在DESY车间以及德国海德堡的马克斯·普朗克研究所中。欧洲分子生物学组织为本文的两位作者——罗森鲍姆和维茨提供了短期奖金。 [英文](#)

（沈乃澍 翻译；尚仁成 审稿）

Estimation of Nuclear Explosion Energies from Microbarograph Records

J. W. Posey and A. D. Pierce

Physicists in the 1970s sought accurate means for estimating the yield of nuclear explosions, especially in tests then being conducted by the United States and the Soviet Union. Here Joe Posey and Allen Pierce report on the accuracy of a new formula they had derived to make such estimates from the detection of very weak air waves from the initial blast. Their formula relates the explosion energy to the peak-to-trough magnitude of the pressure variation in the wave, and also to the $3/2$ power of its period. As they show using data collected for a number of weapons tests conducted in 1961 and 1962, their expression fitted all the data very well, especially for explosions weaker than about 11 megatons.

[中文](#)

FOLLOWING the US and USSR atmospheric test series in 1954–1962, numerous microbarograph records^{1–8} of air waves generated by nuclear bomb tests were published. Previous theoretical interpretations^{7,9} of such waveforms have required some explicit knowledge of the average atmospheric temperature and wind profiles above the path connecting source to microbarograph. Such profiles are never sufficiently well known and vary from point to point, and as

seemingly small changes in the profiles cause relatively large changes in the waveforms, it would seem to be difficult to estimate the explosion energy yield to even order of magnitude accuracy from such records. Recently, however, in a further account of this work to be published elsewhere, we have succeeded in deriving an approximate theoretical relationship between certain waveform features and energy yield which is insensitive to changes in atmospheric structure. This relationship is given by

$$E = 13 p_{\text{FPT}} \left[r_e \sin(r/r_e) \right]^{\frac{1}{2}} H_s (c T_{1,2})^{3/2} \quad (1)$$

where E is energy release, p_{FPT} is the first peak to trough pressure amplitude (see Fig. 1), r_e is radius of the Earth, r is the great circle distance from burst point to observation point, H_s is a lower atmosphere scale height, c is a representative sound speed, and $T_{1,2}$ is the time interval between first and second peaks. The purpose of the present communication is to describe the extent to which the above relation agrees with the existing available data. 中文

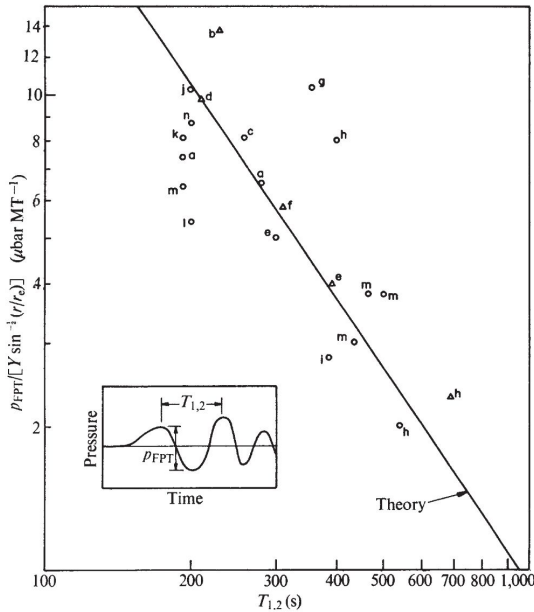


Fig. 1. Comparison of data with the theoretical relationship between amplitude and period of infrasonic waveforms generated by nuclear explosions. The data points are lettered a to n corresponding to particular events defined in the text. $\circ$, Donn and Shaw; Δ , Harkrider.

The various points shown in Fig. 1 correspond to individual microbarograms recorded at Pasadena, California; Berkeley, California; Terceira, Azores; Fletcher's Ice Island; Whippany, New Jersey; Ewa Beach, Hawaii, and Palisades, New York, after the Soviet explosions of (a) September 10 (10 MT), (b) September 11 (9 MT), (c) September 14 (7 MT), (d) October 4 (8 MT), (e) October 6 (11 MT), (f) October 20 (5 MT), (g) October 23 (25 MT), (h) October 30 (58 MT), and (i) October 31, 1961 (8 MT) and the US explosions of (j) May 4 (3 MT), (k) June 10 (9 MT), (l) June 12 (6 MT), (m) June 27 (24 MT), and (n) July 11, 1962 (12 MT). Here the estimate of the yield (in equivalent megatons of TNT where one MT equals 4.2×10^{22} ergs) is taken from Båth¹⁰. All the records used are taken from the articles of Harkrider⁷ and of Donn and Shaw⁸. Pressure amplitudes for Harkrider's records were computed using his microbarograph response data. Pressure amplitudes for the Donn and Shaw records were determined according to the premises (W. Donn, private communication) that (a) all records recorded by Lamont type A microbarographs are to the same scale and (b) the clip to clip amplitude of off scale oscillations was 350 μ bars. The ordinate in Fig. 1 gives $p_{\text{FFT}}/[Y \sin^{-\frac{1}{2}}(r/r_c)]$ in $\mu\text{bar MT}^{-1}$ where Y is the explosion yield in MT. The abscissa gives the period $T_{1,2}$ in s. Note that the plot is full logarithmic. The solid line represents the theoretical relation, equation (1) with c and H_s taken as 310 m s⁻¹ and 8 km, respectively. 中文

The scatter about the theoretical curve could be due to various causes; one which seems especially likely is the undulation in amplitude due to the horizontal refraction and subsequent focusing or defocusing caused by departures of the atmosphere from perfect stratification. We may note also that much of the scatter would not be present if we had omitted data corresponding to explosions of greater than 11 MT. The general trend of longer period signals being of lower amplitudes than signals recorded elsewhere but which were generated by the same

event seems to be amply substantiated by the data.

中文

(232, 253; 1971)

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Received June 17, 1971.

References:

1. Yamamoto, R., *Bull. Amer. Meteorol. Soc.*, **37**, 406 (1956).
2. Araskog, R., Ericsson, U., and Wagner, H., *Nature*, **193**, 970 (1962).
3. Carpenter, E. G., Harwood, G., and Whiteside, T., *Nature*, **192**, 857 (1961).
4. Farkas, E., *Nature*, **193**, 765 (1962).
5. Jones, R., *Nature*, **193**, 229 (1962).
6. Wexler, H., and Hass, W. A., *J. Geophys. Res.*, **67**, 3875 (1962).
7. Harkrider, D. G., *J. Geophys. Res.*, **69**, 5295 (1964).
8. Donn, W., and Shaw, D., *Rev. Geophys.*, **5**, 53 (1967).
9. MacKinnon, R., *Quart. J. Roy. Meteorol. Soc.*, **93**, 436 (1967).
10. Båth, M., Rept. A 4270-4271 (Seismological Institute, Univ. Uppsala, 1962).

根据微压计记录估计出的核爆炸能量

波西，皮尔斯

20世纪70年代，物理学家们曾试图找到一种能精确估计核爆炸输出能量的方法，特别是因为可以在美国和苏联即将实施的核爆炸试验中进行估算。乔·波西和艾伦·皮尔斯在本文中阐述了他们为估计核爆炸能量而推导出来的一个新公式的精确性，这个公式是根据对最初爆炸产生的极弱空气波的测量得到的。他们在公式中将核爆炸输出能量与次声波上的波峰-波谷间压力变化幅度及其周期的3/2次方联系起来。他们利用在1961年和1962年核武器试验之后所采集到的大量数据来说明上述公式与所有数据都符合得很好，尤其是对于输出能量小于11兆吨左右的核爆炸。 [英文](#)

继美国和苏联在1954年至1962年间对大气所作的一系列测试之后，有不少人发表了由核弹试验产生的空气波的微压计记录数据^[1-8]。如果要用以前的理论^[7,9]来解释这些波形，就需要较为确切地知道连接爆炸源和微压计之间路径上方的平均气温和风廓线。这样的风廓线是不可能精确得到的，并且在每一个点上的值都是有所不同的，而且因为风廓线中看似微小的变化就能使波形发生相当大的改变，所以即使只是想要根据这些微压计记录值估计出核爆炸产生能量输出的数量级恐怕也并非易事。然而，我们最近将在别处发表的一篇文章中对此项工作进行进一步的报道——我们成功地推导出了特定波形特征和能量输出之间存在的近似理论关系，这种方法对大气结构变化不是很敏感。其关系式如下：

$$E = 13 p_{\text{FPT}} \left[r_c \sin(r/r_c) \right]^{\frac{1}{2}} H_s (c T_{1,2})^{3/2} \quad (1)$$

式中： E 代表释放出的能量， p_{FPT} 是从第一个波峰到波谷的压力变化幅度（见图1）， r_e 表示地球半径， r 表示从爆炸点到观测点的大圆距离， H_s 表示低层大气标高， c 表示声速，而 $T_{1,2}$ 是第一个波峰与第二个波峰之间的时间间隔。本篇论文的目的在于阐述上述关系式与实际测量数据之间的符合程度。 英文

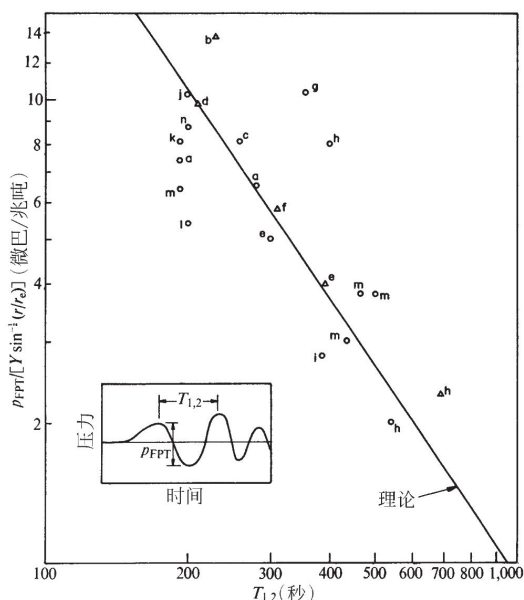


图1. 核爆炸所产生的次声波的振幅和周期数据与理论关系式的对比。其中标有字母a到n的数据点分别对应于文章中所定义的特殊事件。○表示唐和肖的记录数据；△表示哈克赖德的记录数据。 英文

图1中所示的各个点分别对应于：在苏联核爆炸之后于加州帕萨迪纳、加州伯克利、亚速尔群岛特塞拉岛、弗莱彻浮冰岛、新泽西州惠帕尼、夏威夷州埃瓦海滩和纽约州帕利塞兹测量的微压计记录结果，测量时间分别为1961年（a）9月10日（10兆吨），（b）9月11日（9兆吨），（c）9月14日（7兆吨），（d）10月4日（8兆吨），（e）10月6日（11兆吨），（f）10月20日（5兆吨），（g）10月23日（25兆吨），（h）10月30日（58兆吨）和（i）10月31日（8兆吨）；在美国核爆炸之后于上述地点测量的微压计记录结果，时间为1962年（j）5月4日（3兆吨），（k）6月10日（9兆吨），（l）6月12日（6兆吨），（m）6月27日（24兆吨）和（n）7月11日（12兆吨）。本文中对核爆炸能量输出值的估计（相当于多少兆吨三硝基甲苯爆炸所释放的能量，其中1兆吨=4.2×10²²尔格）利用了贝斯的结果^[10]。所有测量记录均来

自哈克赖德^[7]以及唐和肖^[8]的文章。哈克赖德记录值中的压力变化幅度是由他的微压计响应数据计算得到的。唐和肖记录值中的压力变化幅度是根据以下假设得到的（唐，私人交流）：（a）所有用拉蒙特A型微压计所作的记录都采用了同样的标度（b）标度以外振动的削波幅度为350微巴。图1中纵坐标 $p_{\text{FPT}}/[Y\sin^{-\frac{1}{2}}(r/r_c)]$ 的单位为微巴/兆吨，其中爆炸能量输出Y的单位是兆吨。横坐标周期 $T_{1,2}$ 的单位为秒。请注意图1中的横纵坐标均采用对数形式。实线代表由式（1）给出的理论关系，其中c和 H_s 的取值分别为310米/秒和8千米。 [英文](#)

理论曲线的发散可能是由多种原因造成的，其中有一个可能性非常大，即由地平大气折射以及随之而来的因大气层偏离理想层而产生的聚焦或散焦所导致的振幅波动。我们也注意到：如果忽略大于11兆吨的爆炸所对应的数据，那么大部分发散将不复存在。由上述数据似乎足以证明这样的趋势：对于由同样事件产生的信号，周期较长信号的幅度要低于在别处记录的信号的幅度。 [英文](#)

（韩少卿 翻译；尚仁成 审稿）

Bomb ^{14}C in the Human Population

R. Nydal *et al.*

Understanding the cycling of carbon between the atmosphere, oceans and biosphere (owing mostly to the uptake of carbon dioxide in photosynthesis) is essential for predicting how anthropogenic greenhouse gases affect climate. This paper from scientists at the Norwegian Institute of Technology shows how interest in the carbon cycle was already burgeoning in the early 1970s. It is expressed within the context of its time: it focuses on how the radioactive isotope carbon-14 (^{14}C), released into the atmosphere by nuclear weapons tests, will increase in the human body, which was considered a potential health risk. Strikingly, this increase is very short-lived, because the bomb ^{14}C is rapidly diluted by carbon dioxide released from fossil-fuel burning—today considered a much greater hazard. [中文](#)

IN the atmosphere ^{14}C occurs principally as $^{14}\text{CO}_2$ and is usually produced by nuclear reactions between cosmic ray neutrons and the nitrogen atoms of the air. The natural equilibrium between production and disintegration of ^{14}C determines a part of the natural background radiation to the human population. From 1955 there has been a gradual increase of ^{14}C in the atmosphere, the land biosphere and the ocean, as a result of nuclear tests. Although ^{14}C was initially not regarded as an important hazard to man¹, it was later pointed out²⁻⁴

that ^{14}C could be a source of appreciable genetic hazard in the world's population, because of its long half life (5,700 yr). 中文

At this laboratory we have studied the ^{14}C concentration in the human body⁵. The correspondence between ^{14}C in the atmosphere and in the human body, mediated as it is by photosynthesis, has been confirmed in 6 yr of measurements⁶⁻⁸. 中文

Since 1955, about two-thirds of the total nuclear energy liberated in nuclear tests has resulted from tests carried out in the atmosphere at high northern latitudes in 1961 and 1962 (ref. 9). The subsequent transfer of ^{14}C down to the troposphere, the biosphere and the ocean has been followed in detail¹⁰⁻¹⁶. The ^{14}C excess¹⁶ ($\delta^{14}\text{C}$) in the northern troposphere (Fig. 1) is representative chiefly of the region between 30°N and 90°N , although the curve for the southern troposphere is representative of the region from the equator to 90°S .

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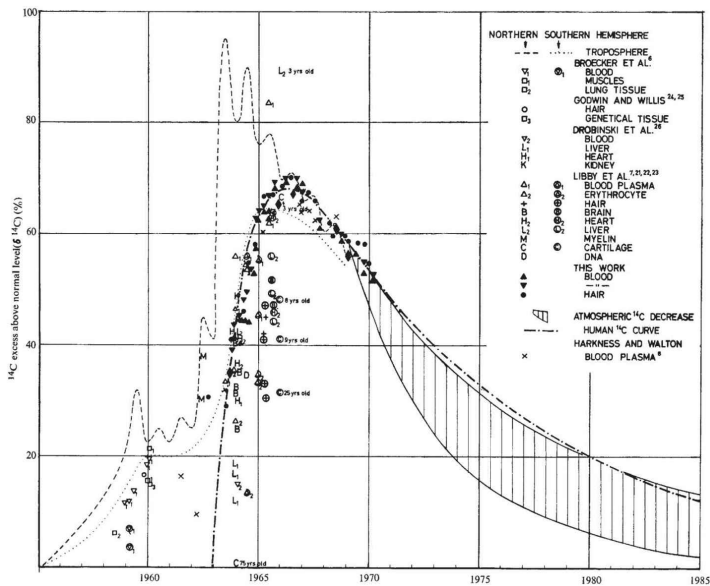


Fig. 1. Radiocarbon in the troposphere and human body. 中文

The model for CO_2 exchange between the various reservoirs is shown in Fig. 2, in which the CO_2 in the troposphere is in exchange with CO_2

in the stratosphere, the land biosphere and the ocean. For CO_2 exchange between the troposphere and the biosphere we share the view of Münnich (for discussion, see ref. 17), who divided the biosphere into two parts. The first (b_1), which consists of leaves, grass, branches, and so on, is in rapid exchange with the troposphere and is combined with this reservoir, but the larger part of the vegetation (b_2) has a much slower exchange rate and is combined with the humus layer.

中文

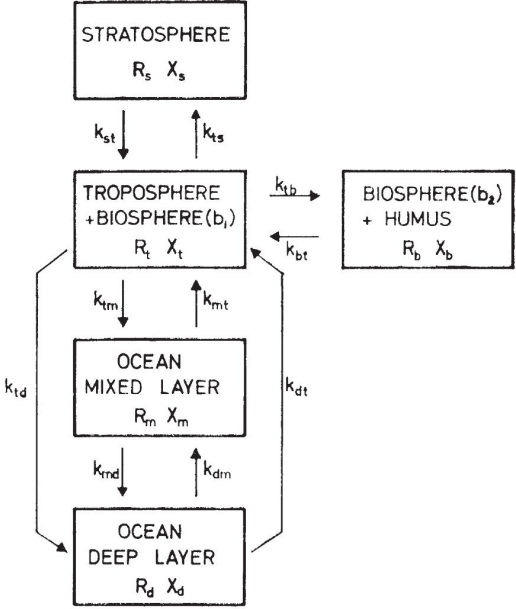


Fig. 2. Exchangeable carbon reservoirs, where: R_i , total carbon amount; X_i , ^{14}C excess; k_{ij} , exchange coefficients; i, j, t, b, m, d ($i \neq j$).

中文

The ocean is divided into two reservoirs, the mixed layer and the deep ocean. The exchange of CO_2 between the troposphere and the ocean occurs chiefly in the mixed layer, but according to Craig¹⁸ there is also the possibility of a direct exchange with the deep ocean. The ^{14}C concentration in the mixed layer of the ocean is now 10 to 15% above normal^{19,20}.

中文

Using the model of Fig. 2, we have treated the decrease of $\delta^{14}\text{C}$ in the troposphere in a previous article²⁰. We showed that the measured

variation of $\delta^{14}\text{C}$ (x_t) in the troposphere is approximately reproduced by the following two-term exponential function:

$$x_t = A_1 e^{-k_1 t} + A_2 e^{-k_2 t} \quad (1)$$

in which the parameters A_1 , A_2 , k_1 and k_2 depend on the various exchange coefficients. Because the errors on some of these coefficients are large, the extrapolation is uncertain and is given in the shaded area of Fig. 1. [中文](#)

The amount of bomb-produced ^{14}C in the atmosphere has increased the total natural amount of ^{14}C in nature by about 3%. According to Harkness *et al.*⁸, the production of CO_2 from fossil fuel would lower the natural ^{14}C concentration in the atmosphere to about 16% below normal at the end of this century. It is thus reasonable that the ^{14}C excess caused by the atomic bomb will be more than compensated for by the dilution of inactive carbon (the Suess effect). [中文](#)

The transfer of ^{14}C into the human body depends on the following three factors: (1) the time between the photosynthesis in vegetational food and its consumption; (2) the diet, particularly the amount of vegetational food, and (3) the residence time of the carbon in the constituents of human tissue. [中文](#)

Broecker *et al.*⁶ (Fig. 1) found that it took 1 and 1.8 yr before the ^{14}C concentration in blood and lung tissue, respectively, reached that in the atmosphere. They also found that the $\delta^{14}\text{C}$ value of blood had a maximum time lag of 6 months behind food. [中文](#)

Berger and collaborators^{7,21-23} (Fig. 1) studied chiefly the metabolic turnover time of the constituents of human tissue. For this they used samples from persons who had travelled from the southern to the northern hemisphere. One result of their work was that the

incorporation in these people of ^{14}C in brain protein and lipids, liver, heart, plasma protein and erythrocyte protein was very similar to, and reflected, the atmospheric ^{14}C content present several months earlier. Collagen of cartilage was found to be metabolically inert in older persons. The concentration of ^{14}C in the human body has been studied by other workers (refs. 8, 24–26) who obtained values shown in Fig.

1. 中文

At our laboratory the transfer of ^{14}C into the human body was studied by following the time-variation of $\delta^{14}\text{C}$ in blood and hair for three persons^{5,27} (Tables 1–3). No separation between blood plasma and erythrocyte protein was performed, and the measured ^{14}C activity is thus a mean value for the total blood samples. Fig. 1 shows that there is excellent agreement between data obtained for the blood and for the hair samples. The values of the ^{14}C concentration in blood plasma obtained by Harkness and Walton⁸ are slightly lower than ours.

中文

Table 1. Carbon in Neck Hair, from a Boy (K.N.) Born in 1962

Time of collection	$\delta^{13}\text{C} \%$	$\delta^{13}\text{C}/\text{‰}$	$\Delta^{13}\text{C} \%$
November 1962	30.7 ± 1.3		
June 1963	29.2 ± 0.8	-19.7	26.7
October 1963	41.0 ± 1.0	$-19.2 \uparrow$	39.3
March 1964	46.0 ± 1.0	-18.9	44.2
July 1964	54.8 ± 1.0	$-19.2 \uparrow$	52.9
October 1964	58.0 ± 0.8	-18.6	55.9
February 1965	66.9 ± 1.0	$-19.2 \uparrow$	64.9
July 1965	67.2 ± 1.0	-18.6	64.5
February 1966	68.7 ± 1.0	-19.2	66.7
May 1966	70.0 ± 0.9	$-19.2 \uparrow$	68.0
December 1966	65.9 ± 0.9	$-19.2 \uparrow$	63.9
February 1967	67.5 ± 1.1	$-19.2 \uparrow$	65.4
July 1967	65.9 ± 0.9	$-19.2 \uparrow$	63.9
February 1968	61.5 ± 0.9	$-19.2 \uparrow$	59.6
May 1968	60.2 ± 1.1	$-19.2 \uparrow$	58.2
August 1968	61.8 ± 1.2	$-19.2 \uparrow$	59.9
November 1968	59.7 ± 1.1	$-19.2 \uparrow$	57.7
January 1969	58.7 ± 1.2	$-19.2 \uparrow$	56.7
April 1969	58.2 ± 1.2	$-19.2 \uparrow$	56.5
May 1969	58.3 ± 1.2	$-19.2 \uparrow$	56.6
July 1969	58.1 ± 1.1	$-19.2 \uparrow$	56.4
October 1969	54.9 ± 0.9	$-19.2 \uparrow$	53.1
December 1969	54.7 ± 1.1	$-19.2 \uparrow$	52.9

† Not measured (mean value). 中文

Table 2. Carbon in Blood Samples, from a Woman (I.N.), 26 Yr Old in 1963

Time of collection		$\delta^{13}\text{C} \text{ ‰}$	$\delta^{13}\text{C}/\text{‰}$	$\Delta^{13}\text{C} \text{ ‰}$
September	1963	34.9 ± 1.1	-22.0	34.0 ± 1.1
October	1963	39.3 ± 0.8	-22.2	38.5 ± 0.8
November	1963	43.6 ± 0.8	-22.7	42.9 ± 0.9
February	1964	45.6 ± 1.1	-22.0	44.7 ± 1.2
April	1964	48.1 ± 1.1	-21.7	47.1 ± 1.1
June	1964	49.6 ± 1.1	-21.7†	48.6 ± 1.1
July	1964	53.7 ± 1.0	-22.1	52.8 ± 1.1
November	1964	62.9 ± 0.9	-19.8	61.2 ± 0.9
January	1965	64.2 ± 0.9	-19.7	62.4 ± 0.9
March	1965	65.0 ± 0.9	-20.5	63.5 ± 1.0
May	1965	67.1 ± 1.0	-21.1	65.6 ± 1.0
September	1965	69.1 ± 0.9	-22.0	67.9 ± 1.0
November	1965	65.6 ± 0.9	-21.4	64.2 ± 1.0
March	1966	69.7 ± 0.9	-22.3	68.7 ± 0.9
July	1966	67.6 ± 1.1	-21.2	66.2 ± 1.1
September	1966	69.8 ± 1.0	-21.5	68.6 ± 1.1
December	1966	67.4 ± 1.0	-21.9	66.3 ± 1.0
September	1967	62.5 ± 0.9	-21.7†	61.4 ± 0.9
June	1968	60.6 ± 0.9	-21.7†	59.5 ± 1.0
August	1968	59.9 ± 0.9	-21.7†	58.8 ± 1.0
January	1969	56.0 ± 0.7	-21.7†	55.0 ± 0.7
September	1969	55.5 ± 1.2	-21.7†	54.5 ± 1.2
March	1970	52.6 ± 1.2	-21.7†	51.6 ± 1.2

† Not measured (mean value). 中文

Table 3. Carbon in Blood Samples, from a Woman (A.L.), 26 Yr Old in 1963

Time of collection		$\delta^{14}\text{C} \text{ ‰}$	$\delta^{13}\text{C}/\text{‰}$	$\Delta^{13}\text{C} \text{ ‰}$
September	1963	35.2 ± 0.8	-21.6	34.2 ± 0.8
November	1963	41.5 ± 0.6	-21.7†	40.6 ± 0.7
February	1964	40.5 ± 0.6	-20.9	39.3 ± 0.7
March	1964	44.4 ± 0.8	-22.5	43.5 ± 0.9
April	1964	44.2 ± 0.7	-23.2	43.6 ± 0.7
June	1964	44.2 ± 1.0	-22.1	43.3 ± 1.0
August	1964	53.4 ± 0.8	-21.9	52.4 ± 0.9
November	1964	57.6 ± 0.9	-20.7	56.2 ± 0.9
January	1965	62.4 ± 0.9	-19.1	60.5 ± 0.9
March	1965	64.3 ± 0.7	-20.1	62.6 ± 0.7
May	1965	63.9 ± 0.9	-21.0	62.5 ± 1.0
September	1965	68.4 ± 0.9	-22.0	67.3 ± 1.0
November	1965	65.9 ± 0.7	-21.4	64.4 ± 0.8
March	1966	69.6 ± 1.0	-22.0	68.5 ± 1.1
July	1966	67.5 ± 1.0	-21.2	66.2 ± 1.1
September	1966	68.3 ± 1.0	-20.9	66.9 ± 1.0
December	1966	69.0 ± 0.9	-20.8	67.6 ± 1.0
September	1967	60.9 ± 0.9	-21.7†	59.8 ± 0.9
June	1968	61.4 ± 0.9	-21.7†	60.3 ± 0.9
August	1968	58.8 ± 0.9	-21.7†	57.7 ± 0.9
January	1969	56.6 ± 0.7	-21.7†	55.6 ± 0.7
May	1969	56.4 ± 1.0	-21.7†	55.4 ± 1.0
September	1969	53.0 ± 1.0	-21.7†	52.0 ± 1.0
March	1970	51.6 ± 1.1	-21.7†	50.6 ± 1.1

† Not measured (mean value). [中文](#)

The blood and hair data are almost representative for persons living in the northern hemisphere. Because $\delta^{14}\text{C}$ in the southern troposphere at present lags behind that of the northern troposphere by about 1 yr, there should also be a similar lag for $\delta^{14}\text{C}$ in the human populations of the respective hemispheres. After about 1970, the ^{14}C concentrations in people in the northern and southern hemispheres will be similar, and equal to those in the troposphere. Fig. 1 shows that $\delta^{14}\text{C} (x_{\text{H}})$ in the human body appears as a pulse, delayed with respect to that of the atmosphere. The observed values for x_{H} can be fitted reasonably well by the following two-term exponential function:

$$x_{\text{H}} = 108 (e^{-0.1t} - e^{-0.75t}) \tag{2}$$

The coefficients in this function were determined by a least mean squares method, using the upper limits of the measured values for ^{14}C

in the human body in the period from 1963 to 1970, and extrapolated values in the troposphere in the period from 1970 to 2000. The upper limit values were chosen because there was some excess ^{14}C before 1963 which should also be considered. There is also a tendency for the blood and hair data during the last 2 yr to correspond with the upper limit of the shaded area in Fig. 1. Function (2) was simplified by assuming that all previous nuclear tests occurred within a short time interval, and that the ^{14}C increase in the human population started in about January 1963. 中文

The first term in the brackets of equation (2) indicates that the excess ^{14}C in the human body has a mean lifetime of about 10 yr and the second term that ^{14}C enters the human body with a mean delay time of about 1.4 yr after production in the atmosphere. The latter value is probably accurate to within 30% and agrees with previous estimates^{6,7}. 中文

The hazard to the human population from artificial radiocarbon arises largely from inventory radiation of the body. Natural ^{14}C contributes with a certain dose rate, r_0 , as a result of its decay rate of about fourteen disintegrations per min per gram of carbon. The average value of r_0 is about 1.06 mrad/yr⁹. The dose from natural ^{14}C is distributed as follows: 1.64 mrad/yr in the bones, 1.15 mrad/yr in the cells lining bone surfaces and 0.71 mrad/yr in bone marrow and soft tissue. Applying function (2), the dose D_1 absorbed in the human body during a time t can be calculated from the formula:

$$D_1 = 1.08 r_0 \int_0^t (e^{-0.1t} - e^{-0.75t}) dt \quad (3)$$

For a period of about 30 yr the total radiation dose from this source will be $9r_0$. We thus obtain a total radiation dose of 16 mrad to bone, 11 mrad to cells lining bone surfaces and 7 mrad to bone marrow and soft tissue. The genetic hazard is caused by the latter. That dose constitutes about 10% of the total gonad dose from all radioactive

fallout. Purdom⁴ pointed out, however, that the actual gonad dose is somewhat larger because of a transmutation process in the DNA molecule, in which the decaying ¹⁴C atoms are replaced by nitrogen atoms. Purdom assumed that the biological damage from the transmutation was equal to that from β-radiation. 中文

The amount of artificial ¹⁴C in the human body at about the year AD 2000 will constitute about 3% of the total amount of ¹⁴C. This isotope has a half-life of 5,700 yr, and several scientists^{2,3,9,28} think that it would therefore cause a most serious genetic threat. The long term radiation dose can be calculated from the formula

$$D_2 = 0.03 r_0 \int_0^t e^{-0.000125t} dt \quad (4)$$

The total radiation doses ($D_1 + D_2$) which will be received by the bone cells, the cells lining bone surfaces, and the bone marrow and soft tissue in the next 10,000 yr will be 410, 290 and 180 mrad, respectively. These doses, which are in agreement with values given in a United Nations report⁹ (page 45), are more important than those from all other radioactive fallout. We question, however, the value of the long term radiation dose (D_2) because, as previously mentioned, the use of fossil fuel might reduce the ¹⁴C concentration in man below normal. We are of the opinion that the only ¹⁴C hazard from previous tests which should be taken into account is attributable to a total genetic dose (D) of the order of 10 mrad, received in a period of about 30 yr. This dose is, however, negligible compared with the dose received from natural sources, which constitutes about 100 mrad per yr. 中文

We thank Norges Almenvitenskapelige Forskningsråd for financial support. 中文

(232, 418-421; 1971)

Received November 10, 1969; revised August 24, 1970.

References:

1. Libby, W. F., *Science*, **123**, 657 (1956).
2. Pauling, L., *Science*, **128**, 3333 (1958).
3. Sakharow, A. D., *Soviet Scientists on the Danger of Nuclear Tests*, 39 (Foreign Languages Publishing House, Moscow, 1960).
4. Purdom, C. E., *New Scientist*, **298**, 255 (1962).
5. Nydal, R., *Nature*, **200**, 212 (1963).
6. Broecker, W. A., Schulert, A., and Olson, E. A., *Science*, **130**, 331 (1959).
7. Libby, W. F., Berger, R., Mead, J. F., Alexander, G. V., and Ross, J. F., *Science*, **146**, 1170 (1964).
8. Harkness, D. D., and Walton, A., *Nature*, **223**, 1216 (1969).
9. *Rep. UN Sci. Comm. Effect of Atomic Radiation*, No. 14 (A/5814) (United Nations, New York, 1964).
10. Münnich, K. O., and Roether, W., *Proc. Monaco Symp.*, 93 (Vienna, 1967).
11. Bien, G., and Suess, H., *Proc. Monaco Symp.*, 105 (Vienna, 1967).
12. Rafter, T. A., *NZ J. Sci.*, **8**, 4, 472 (1965).
13. Rafter, T. A., *NZ J. Sci.*, **11**, 4, 551 (1968).
14. Young, J. A., and Fairhall, A. W., *J. Geophys. Res.*, **73**, 1185 (1968).
15. Lal, D., and Rama, *J. Geophys. Res.*, **71**, 2865 (1966).
16. Nydal, R., *J. Geophys. Res.*, **73**, 3617 (1968).
17. Nydal, R., *Symp. on Radioactive Dating and Methods of Low-Level Counting*, UN Doc. SM 87/29 (International Atomic Energy Agency, Vienna, 1967).
18. Craig, H., *Second UN Intern. Conf. on the Peaceful Uses of Atomic Energy*, A/CONF. 15/P/1979 (June 1958).
19. Rafter, T. A., and O'Brien, B. J., *Proc. 12th Nobel Symp.* (Almqvist and Wiksell, Uppsala, 1970).
20. Nydal, R., and Lövseth, K., *CACR Symp.* (Heidelberg, 1969); *J. Geophys. Res.*, **75**, 2271 (1970).
21. Berger, R., Fergusson, G. J., and Libby, W. F., *Amer. J. Sci., Radiocarbon Suppl.*, **7**, 336 (1965).
22. Berger, R., and Libby, W. F., *Amer. J. Sci., Radiocarbon Suppl.*, **8**, 467 (1966).
23. Berger, R., and Libby, W. F., *Amer. J. Sci., Radiocarbon Suppl.*, **9**, 477 (1967).
24. Godwin, H., and Willis, E. H., *Amer. J. Sci., Radiocarbon Suppl.*, **2**, 62 (1960).
25. Godwin, H., and Willis, E. H., *Amer. J. Sci., Radiocarbon Suppl.*, **3**, 77 (1961).
26. Drobinski, jun., J. C., La Gotta, D. P., Goldin, A. S., and Terril, jun., J. G., *Health Phys.*, **11**, 385 (1965).
27. Nydal, R., and Lövseth, K., *Nature*, **206**, 1029 (1965).
28. Pauling, L., *Les Prix Nobel*, 296 (1963) (Nobelstiftelsen, Stockholm, 1964).

进入人体的核弹 ^{14}C

尼达尔等

了解碳在大气、海洋和生物圈中的循环（主要归因于生物体在光合作用中对 CO_2 的吸收）对于预测人类活动所产生的温室气体将怎样影响气候相当重要。这篇由挪威技术研究所的科学家们所撰写的文章使我们了解到，在20世纪70年代早期人们是如何开始注意到碳循环的。本文反映了那个年代的焦点问题：由核武器试验释放到大气中的放射性同位素碳-14（ ^{14}C ）在人体中的含量将会增加，这在当时被认为是一种潜在的健康威胁。显然， ^{14}C 含量的增加是非常短暂的，因为核弹产生的 ^{14}C 很快就会被矿物燃料燃烧释放的 CO_2 所稀释，现在人们认为后者才是人类将要面临的更大威胁。 [英文](#)

大气中 ^{14}C 主要以 $^{14}\text{CO}_2$ 的形式存在，通常由宇宙射线中子和大气中的氮原子通过核反应而产生。 ^{14}C 在产生和衰变之间的自然平衡决定了人类所受到的一部分天然本底辐射的大小。由于核试验的原因，从1955年起，大气层、陆地生物圈和海洋中的 ^{14}C 开始逐步增加。虽然起初人们并不认为 ^{14}C 会对人类造成重大危害^[1]，但后来有人指出^[2-4]：由于 ^{14}C 的半衰期很长（5,700年），因而它对人类基因造成一定程度危害的可能性还是存在的。 [英文](#)

在本实验室中，我们研究了人体内的 ^{14}C 浓度^[5]。经过6年时间的测试，我们已证实大气中的 ^{14}C 与人体中的 ^{14}C 是相互关联的，它们之间的媒介是光合作用^[6-8]。 [英文](#)

自1955年起到现在，从核试验中释放出来的全部核能的2/3左右来自于1961年和1962年人们在北纬高纬度地区大气层中所进行的试验（参考文献9）。有不少人对 ^{14}C 接下来向对流层、生物圈和海洋中的转移进行了详细的报道^[10-16]。北半球对流层中 ^{14}C 的过量值^[16]（ $\delta^{14}\text{C}$ ）

主要针对从北纬30°到北纬90°之间的区域（图1），而南半球对流层曲线所代表的区域则是从赤道到南纬90°之间。

英文

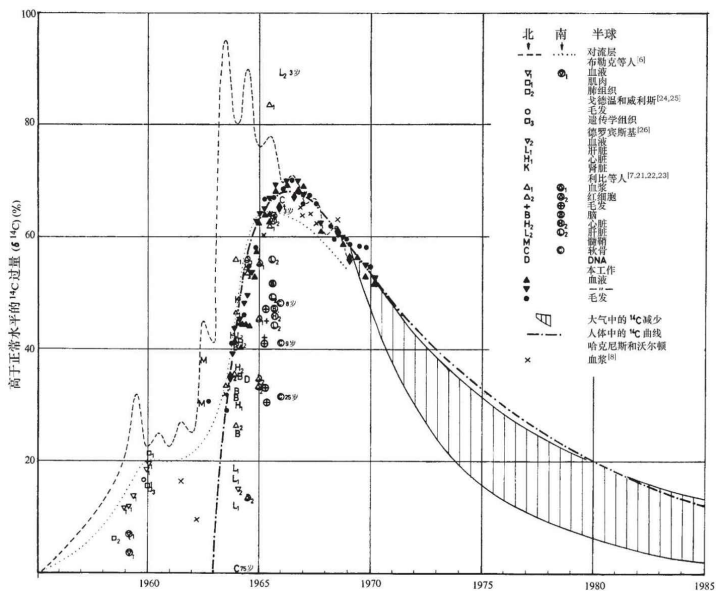


图1．在对流层和人体中的放射性碳

英文

CO₂在不同碳库之间的交换模型如图2所示。从图中可以看出，对流层中的CO₂会与平流层、陆地生物圈和海洋之中的CO₂发生交换。就CO₂在对流层和生物圈之间的交换而言，我们赞同明尼希的观点，即认为生物圈可以被分为两个部分（讨论过程见参考文献17）。第一部分（b₁）由树叶、草、树枝等组成，这部分与对流层之间发生着快速的交换并且与之结合；但相当多的植物属于第二部分（b₂），这部分与对流层之间的交换速率很慢并且是和腐殖质层结合在一起的。

英文

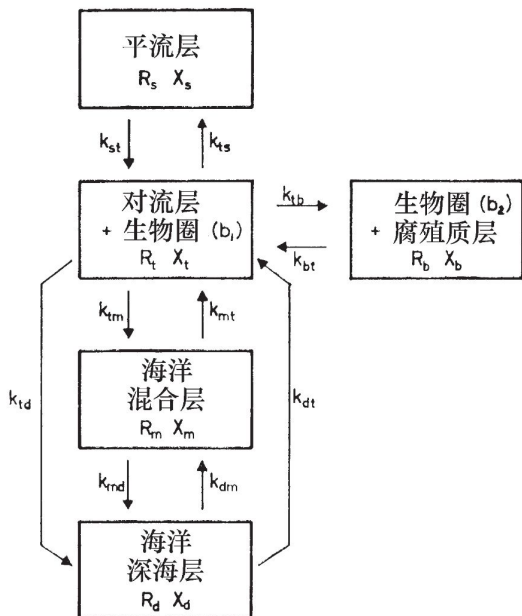


图2. 可进行交换的碳库，其中： R_i 为总碳量； X_i 为 ^{14}C 过量； k_{ij} 为交换系数； i, j 代表 t, b, m, d ($i \neq j$)。

英文

海洋被分成两个碳库，分别是混合层和深海层。 CO_2 在对流层和海洋之间的交换主要发生在混合层，但根据克雷格的说法^[18]，直接交换也可能会发生在对流层和深海层之间。目前在海洋混合层中的 ^{14}C 浓度要高出正常值10%~15%^[19,20]。

英文

在之前发表的一篇文章中^[20]，我们利用图2的模型讨论了对流层中 $\delta^{14}\text{C}$ 的下降。我们认为，对流层中 $\delta^{14}\text{C}$ (x_t) 测量值的变化可大致由以下这个包含两项指数函数的式子来模拟：

$$x_t = A_1 e^{-k_1 t} + A_2 e^{-k_2 t}$$

(1)

其中，参数 A_1 、 A_2 、 k_1 和 k_2 由不同的交换系数决定。因为其中有一些系数误差很大，所以外推结果有一定的变化范围，在图1中用阴影部分表示。

英文

核弹在大气中产生的 ^{14}C 已使自然界中 ^{14}C 的天然总含量增加了约3%。根据哈克尼斯等人的说法^[8]：到本世纪末，由矿物燃料产生的 CO_2

将使大气中的天然 ^{14}C 浓度下降到比正常值低大约16%的水平。因此，我们可以合理地推出，非放射性碳的稀释作用完全可以补偿由核弹引起的 ^{14}C 过量（苏斯效应）。 [英文](#)

^{14}C 向人体内的迁移过程取决于以下三个因素：（1）从植物性食物进行光合作用到它被人类食用之间的时间；（2）饮食结构，尤其是植物性食物所占的比重；（3）碳在人体组织各组成成分中的滞留时间。

[英文](#)

布勒克等人^[6]（图1）发现：要使血液和肺组织中的 ^{14}C 浓度达到大气中的浓度分别需要1年和1.8年的时间。他们还发现，从进食到血液中出现 $\delta^{14}\text{C}$ 之间的最大时间滞后可达6个月。 [英文](#)

伯杰及其合作者^[7,21-23]（图1）重点研究了人体组织各组成成分的新陈代谢周转时间。他们为此选用的样本均来自于那些有过从南半球到北半球旅行经历的人。他们获得的一项研究成果显示： ^{14}C 与这些人的脑蛋白以及脂类、肝、心、血浆蛋白和红细胞蛋白的结合情况非常接近于数月前大气中的 ^{14}C 含量，可以认为它能够反映数月前大气中的 ^{14}C 含量。他们发现老年人软骨组织中的胶原蛋白具有新陈代谢惰性。图1中还显示出了一些由其他研究者（参考文献8及24~26）得到的人体中的 ^{14}C 浓度值。 [英文](#)

在我们的实验室，对 ^{14}C 进入人体的研究是通过跟踪3个人血液和毛发中 $\delta^{14}\text{C}$ 随时间的变化来进行的^[5,27]（表1~表3）。因为没有对血液中的血浆和红细胞进行分离，所以测得的 ^{14}C 放射性是整个血样的平均值。从图1中可以看出，由血样得到的数据和由毛发样本得到的数据吻合得非常好。哈克尼斯和沃尔顿测得的血浆中的 ^{14}C 浓度数据^[8]略微低于我们测得的值。 [英文](#)

表1. 颈部毛发中的碳，来自于一个1962年出生的男孩（K.N.）

采集时间	$\delta^{14}\text{C} \%$	$\delta^{13}\text{C}/\text{‰}$	$\Delta^{14}\text{C} \%$
1962 年 11 月	30.7 ± 1.3		
1963 年 6 月	29.2 ± 0.8	-19.7	26.7
1963 年 10 月	41.0 ± 1.0	-19.2†	39.3
1964 年 3 月	46.0 ± 1.0	-18.9	44.2
1964 年 7 月	54.8 ± 1.0	-19.2†	52.9
1964 年 10 月	58.0 ± 0.8	-18.6	55.9
1965 年 2 月	66.9 ± 1.0	-19.2†	64.9
1965 年 7 月	67.2 ± 1.0	-18.6	64.5
1966 年 2 月	68.7 ± 1.0	-19.2	66.7
1966 年 5 月	70.0 ± 0.9	-19.2†	68.0
1966 年 12 月	65.9 ± 0.9	-19.2†	63.9
1967 年 2 月	67.5 ± 1.1	-19.2†	65.4
1967 年 7 月	65.9 ± 0.9	-19.2†	63.9
1968 年 2 月	61.5 ± 0.9	-19.2†	59.6
1968 年 5 月	60.2 ± 1.1	-19.2†	58.2
1968 年 8 月	61.8 ± 1.2	-19.2†	59.9
1968 年 11 月	59.7 ± 1.1	-19.2†	57.7
1969 年 1 月	58.7 ± 1.2	-19.2†	56.7
1969 年 4 月	58.2 ± 1.2	-19.2†	56.5
1969 年 5 月	58.3 ± 1.2	-19.2†	56.6
1969 年 7 月	58.1 ± 1.1	-19.2†	56.4
1969 年 10 月	54.9 ± 0.9	-19.2†	53.1
1969 年 12 月	54.7 ± 1.1	-19.2†	52.9

†未测量（平均值）。 [英文](#)

表2. 血样中的碳，来自于一位在1963年时年龄为26岁的妇女（I.N.）

采集时间	$\delta^{14}\text{C} \%$	$\delta^{13}\text{C}/\text{‰}$	$\Delta^{14}\text{C} \%$
1963 年 9 月	34.9 ± 1.1	-22.0	34.0 ± 1.1
1963 年 10 月	39.3 ± 0.8	-22.2	38.5 ± 0.8
1963 年 11 月	43.6 ± 0.8	-22.7	42.9 ± 0.9
1964 年 2 月	45.6 ± 1.1	-22.0	44.7 ± 1.2
1964 年 4 月	48.1 ± 1.1	-21.7	47.1 ± 1.1
1964 年 6 月	49.6 ± 1.1	-21.7†	48.6 ± 1.1
1964 年 7 月	53.7 ± 1.0	-22.1	52.8 ± 1.1
1964 年 11 月	62.9 ± 0.9	-19.8	61.2 ± 0.9
1965 年 1 月	64.2 ± 0.9	-19.7	62.4 ± 0.9
1965 年 3 月	65.0 ± 0.9	-20.5	63.5 ± 1.0
1965 年 5 月	67.1 ± 1.0	-21.1	65.6 ± 1.0
1965 年 9 月	69.1 ± 0.9	-22.0	67.9 ± 1.0
1965 年 11 月	65.6 ± 0.9	-21.4	64.2 ± 1.0
1966 年 3 月	69.7 ± 0.9	-22.3	68.7 ± 0.9
1966 年 7 月	67.6 ± 1.1	-21.2	66.2 ± 1.1
1966 年 9 月	69.8 ± 1.0	-21.5	68.6 ± 1.1
1966 年 12 月	67.4 ± 1.0	-21.9	66.3 ± 1.0
1967 年 9 月	62.5 ± 0.9	-21.7†	61.4 ± 0.9
1968 年 6 月	60.6 ± 0.9	-21.7†	59.5 ± 1.0
1968 年 8 月	59.9 ± 0.9	-21.7†	58.8 ± 1.0
1969 年 1 月	56.0 ± 0.7	-21.7†	55.0 ± 0.7
1969 年 9 月	55.5 ± 1.2	-21.7†	54.5 ± 1.2
1970 年 3 月	52.6 ± 1.2	-21.7†	51.6 ± 1.2

†未测量（平均值）。 [英文](#)

表3. 血样中的碳，来自于一位在1963年时年龄为26岁的妇女（A.L.）

采集时间	$\delta^{14}\text{C} \%$	$\delta^{13}\text{C} / \text{‰}$	$\Delta^{14}\text{C} \%$
1963 年 9 月	35.2 ± 0.8	-21.6	34.2 ± 0.8
1963 年 11 月	41.5 ± 0.6	-21.7†	40.6 ± 0.7
1964 年 2 月	40.5 ± 0.6	-20.9	39.3 ± 0.7
1964 年 3 月	44.4 ± 0.8	-22.5	43.5 ± 0.9
1964 年 4 月	44.2 ± 0.7	-23.2	43.6 ± 0.7
1964 年 6 月	44.2 ± 1.0	-22.1	43.3 ± 1.0
1964 年 8 月	53.4 ± 0.8	-21.9	52.4 ± 0.9
1964 年 11 月	57.6 ± 0.9	-20.7	56.2 ± 0.9
1965 年 1 月	62.4 ± 0.9	-19.1	60.5 ± 0.9
1965 年 3 月	64.3 ± 0.7	-20.1	62.6 ± 0.7
1965 年 5 月	63.9 ± 0.9	-21.0	62.5 ± 1.0
1965 年 9 月	68.4 ± 0.9	-22.0	67.3 ± 1.0
1965 年 11 月	65.9 ± 0.7	-21.4	64.4 ± 0.8
1966 年 3 月	69.6 ± 1.0	-22.0	68.5 ± 1.1
1966 年 7 月	67.5 ± 1.0	-21.2	66.2 ± 1.1
1966 年 9 月	68.3 ± 1.0	-20.9	66.9 ± 1.0
1966 年 12 月	69.0 ± 0.9	-20.8	67.6 ± 1.0
1967 年 9 月	60.9 ± 0.9	-21.7†	59.8 ± 0.9
1968 年 6 月	61.4 ± 0.9	-21.7†	60.3 ± 0.9
1968 年 8 月	58.8 ± 0.9	-21.7†	57.7 ± 0.9
1969 年 1 月	56.6 ± 0.7	-21.7†	55.6 ± 0.7
1969 年 5 月	56.4 ± 1.0	-21.7†	55.4 ± 1.0
1969 年 9 月	53.0 ± 1.0	-21.7†	52.0 ± 1.0
1970 年 3 月	51.6 ± 1.1	-21.7†	50.6 ± 1.1

†未测量（平均值）。 [英文](#)

来自血液和毛发的数据基本上代表了生活在北半球的所有人。因为南半球对流层的 $\delta^{14}\text{C}$ 值比北半球对流层滞后大约1年，所以居住在两个半球的人体内的 $\delta^{14}\text{C}$ 值也应该存在类似的滞后。大致到1970年之后， ^{14}C 在南北半球的人体内的浓度将会趋于持平，并等于对流层中的 ^{14}C 浓度。从图1中可以看出：人体内部的 $\delta^{14}\text{C}$ （ x_{H} ）值就像一个落后于大气中 $\delta^{14}\text{C}$ 值的脉冲。用以下这个包含两项指数函数的式子可以很好地拟合 x_{H} 的观测值：

$$x_{\text{H}} = 108 (e^{-0.1t} - e^{-0.75t}) \tag{2}$$

函数式中的系数是通过最小均方法得到的，用到了在1963年~1970年间测得的人体中 ^{14}C 的上限值，以及将对流层的数据外推到1970年~2000年时的数据。选择上限值是因为还应当考虑到1963年以前的一些 ^{14}C 过量。在最近两年内得到的血液和毛发数据趋向于与图1阴影部分的上限

值相符。化简式（2）的依据是以下两个假设：假设之前所有的核试验都集中发生在一个很短的时间间隔内，并且假设人体中 ^{14}C 含量开始增加的时间大约在1963年1月。 [英文](#)

式（2）括号内的第一项表明，人体内过量 ^{14}C 的平均寿命大约为10年；第二项表明， ^{14}C 从在大气中产生到进入人体之间会有平均1.4年左右的时间滞后。滞后值的精确度大约可以达到30%以内，并与以前文献中的估计值相符^[6,7]。 [英文](#)

人造放射性碳对人类造成的危害主要来源于人体内的辐射量。天然 ^{14}C 的剂量率 r_0 是一个固定值，由它的衰变速率——每克碳每分钟衰变约14次——决定。 r_0 的平均值大致是1.06毫拉德/年^[9]。天然 ^{14}C 的剂量是这样分布的：在骨骼中为1.64毫拉德/年，在骨骼表层细胞中为1.15毫拉德/年，在骨髓和软组织中为0.71毫拉德/年。根据函数式（2），人体在 t 时间内吸收的剂量 D_1 可由下式计算：

$$D_1 = 1.08 r_0 \int_0^t (e^{-0.1t} - e^{-0.75t}) dt \quad (3)$$

在大约30年内，来自该辐射源的总辐射剂量将为 $9r_0$ 。因此我们的骨骼所接受的辐射剂量为16毫拉德，骨骼表层细胞为11毫拉德，骨髓和软组织为7毫拉德。7毫拉德的剂量会对基因造成危害。这一剂量大致等于生殖腺从所有放射性尘埃中所吸收的总剂量的10%。但珀德姆^[4]指出：实际上生殖腺所接收到的辐射剂量还要更大一些，因为DNA分子会发生嬗变，在嬗变过程中产生衰变的 ^{14}C 原子被替换成了N原子。珀德姆认为该嬗变过程对生物造成的伤害就相当于 β 辐射对生物的伤害。 [英文](#)

到大约公元2000年时，人体中的人造 ^{14}C 量将占到 ^{14}C 总量的3%左右。这种同位素的半衰期为5,700年，因而有几位科学家^[2,3,9,28]认为它将对人类基因造成严重的威胁。长期的辐射剂量可由下式计算：

$$D_2 = 0.03 r_0 \int_0^t e^{-0.000125t} dt \quad (4)$$

在未来的10,000年里，由骨骼细胞、骨骼表层细胞以及骨髓和软组织所吸收的总辐射剂量（ $D_1 + D_2$ ）分别为410、290和180毫拉德。这些剂量

与一份联合国报告^[9]（第45页）中给出的值一致，它们比所有其他的放射性尘埃都更重要。然而，我们对长期辐射剂量（ D_2 ）有所怀疑，因为正如我们之前曾经提到的，矿物燃料的使用可能会导致人体中的 ^{14}C 浓度降低至正常水平以下。我们认为：在大约30年内，由以前有足够规模的核试验所造成的 ^{14}C 危害对总遗传剂量（ D ）的贡献只有10毫拉德数量级。而从天然源中吸收的剂量约为100毫拉德/年，可见，与天然源相比，人工源的剂量是不值一提的。 英文

感谢挪威自然和人文科学研究理事会为我们提供了经费上的支持。

英文

（邓铭瑞 翻译；刘京国 审稿）

Statistical Mechanics and Quantum Mechanics

G. E. Uhlenbeck

Nature here reprints a notable address given by physicist George Uhlenbeck in a ceremony awarding him the Lorentz Medal of the Royal Netherlands Academy of Science. Uhlenbeck describes his long-standing interest in fundamental questions of statistical mechanics, and notes that while the foundational problems of quantum theory had occupied theorists for decades, phase transitions—such as the abrupt gas-liquid transition—and related phenomena continued to pose many unsolved problems. Uhlenbeck also claims that the idea of a generally apparent frontier of science—separating the known from the unknown—is mostly a romantic illusion. Instead, he suggests, there are always many frontiers, and they usually become identified whenever there is an advance, not the other way around. [中文](#)

ARE the problems of statistical mechanics truly fundamental? I have often changed my opinion and now I would like to elaborate on it. When I was a young student, kinetic theory of matter seemed to me an example of a theory which truly explains something. With much care and effort I worked my way through the *Lectures on Gas Theory* by Boltzmann and the *Elementary Principles of Statistical Mechanics* by Gibbs. Much escaped me and became clear only after I read the famous encyclopaedia article by the Ehrenfests. It was a revelation,

not only because of its great clarity but also because it contained a careful summing up of the series of more than twelve *lacunae* in the work of the masters. These were like frontier posts and a young student could thereby learn where the real problems lay. How difficult it is to find this out nowadays. The present pollution of the scientific literature makes the finding of clear water, the fundamental concepts, an extremely time consuming occupation. This is true not only for the new student but for anyone who tries to learn something outside his own speciality, as I well know by experience. 中文

Though I passed my examinations successfully, I knew very little of quantum theory and even less of the theory of spectra. I learned that, with Goudsmit's help, when I returned from Rome in 1925 and became Ehrenfest's assistant. I shall not elaborate on the collaboration with Goudsmit, which I shall never forget and which led to the discovery of electron spin. Both Goudsmit and I have often related our memories of this unforgettable period and I mention it only because at that time my conception of statistical mechanics changed completely. I considered it to be clearly on a secondary level. Quantum mechanics on the other hand provided a foundation from which everything should follow, including the behaviour of gases, liquids and solids. This seemed to be confirmed by the success of the electron theory of metals. Pauli and Sommerfeld (both recipients of the Lorentz Medal) showed how all difficulties disappeared as soon as one applied the true quantum statistics. A few riddles remained, such as superconductivity, but in our optimism we felt sure that all would be straightened out eventually. My dissertation in 1927 about statistical methods in quantum theory was therefore a kind of optimistic synthesis of the encyclopaedia article of the Ehrenfests and the new quantum mechanical ideas. The number of unproved assumptions was reduced to three. 中文

Later in Ann Arbor, the beautiful experiments of N. H. Williams on

thermal noise and shot noise aroused my interest in the theory of Brownian motion, one of the nicest applications of statistical mechanics. I thought it very interesting but of course it was not fundamental. I remember very well that when I told Pauli about it he called it “desperation physics”. I didn’t like this but I really agreed with him. For a physicist of the quantum mechanics generation to which I also belonged, the fundamental problems of the 1930s were the theory of the positron, quantum electrodynamics and the developing theories of nuclear structure and beta radioactivity; these were the things on which to work. 中文

Let me say at this juncture that the image of progress in science as a kind of conquest of an unknown domain with a definite “frontier” and successive “breakthroughs” seems to me more and more to be only a romantic illusion. This picture was clearly inspired by the great breakthrough of quantum mechanics and it has influenced my judgment for a long time. I might even say that I was afflicted by it.

中文

My opinion about the fundamental character of statistical mechanics began to change in 1937 to 1938 when I, together with Boris Kahn, became involved in the so called condensation theory. The question why a gas condenses below a sharply determined critical temperature at a sharply determined density has never been called to attention since Van der Waals and the proper understanding of it seemed difficult to us. During the lively discussion about this question at the Van der Waals Congress in 1938 it was even doubted whether the basic assumptions of statistical mechanics contained the answer even in principle. This doubt was not justified, but it made a deep impression on me. As long as such common phenomena as the equilibrium between liquid and vapour and the existence of a critical temperature were not truly understood, the field was not yet conquered, not everything had been explained in principle and thus

there existed fundamental aspects of statistical mechanics which I had not appreciated. [中文](#)

(When I showed Pauli the article by Kahn and myself on condensation theory he looked at it and said, “Yes, one should read this”. He did so and ridiculed somewhat the quasi-mathematical rigour of our work but I believe that he appreciated the fundamental character of the problem.) [中文](#)

After the war, I continued to follow the new developments in quantum electrodynamics and the theory of beta radioactivity, and from time to time I contributed a little. But my interest moved more and more towards the fundamental questions of statistical mechanics. In the 1950s I began to write a book on statistical mechanics with my pupil and friend, the late T. H. Berlin. I hoped that it would become a modernized and expanded version of the encyclopaedia article which had made such an impression on me. I hoped that we could determine the foundations of the theory in the same critical way as the Ehrenfests, and that we could make clear the nature of the still unsolved basic problems. In short, I hoped that we could discover the “structure” of statistical mechanics. [中文](#)

We worked hard on it but did not get very far and the sudden death of Ted Berlin in 1962 makes it doubtful that our plan will ever be realized. I have learned a lot from it, however, and I have the feeling that I more or less understand the structure of classical statistical mechanics at least. I believe that one always has to keep in mind that the task of statistical mechanics is to study the relationship between the macroscopic description of physical phenomena and the microscopic molecular description. These two pictures are in a certain sense independent; moreover, they are, so to speak, on a different level and are therefore, even qualitatively, totally different. If one sticks to this idea, one can see that Boltzmann, Gibbs, Einstein, Ehrenfest and Smoluchowski have formulated the true basis on which

one has to build further. One sees also that there are still many unsolved problems, such as condensation and other so called phase transitions, on which much work is being done. All these problems are very difficult but they are, as a mathematician would say, *bien posés* and therefore one can work on them. 中文

In my opinion the situation is somewhat different for quantum theory. The relationship between the classical and quantum mechanical descriptions of molecular phenomena is rather clear, but this is not so for quantum mechanics and the macroscopic theory. I am aware that this opinion is not shared by most of my colleagues. I believe that the most widespread opinion is that quantum mechanics can be “grafted” onto the classical statistical mechanics of Boltzmann and Gibbs and that therefore quantum mechanics does not require anything essentially new. I had thought so earlier too, but I have slowly retreated from that conviction. The recent discoveries of so called macroscopic quantization and interference phenomena in liquid helium and superconductors have had a great influence on my ideas. They seem to me to show that the existing theories of superconductivity and superfluidity do not provide a complete explanation and that the true macroscopic description of the superfluids has not yet been found. It would be no surprise to me that this is so because the foundations of quantum statistical mechanics have not yet been sufficiently clarified. One only needs to think of the persistent currents to feel doubt about the general validity of the ergodic theorems in quantum theory. Questions like these make low temperature physics so fascinating for me; they have had a rejuvenating effect on me and I am convinced that there is still much to be done on this “frontier” of physics and that profound surprises are possible. 中文

Because I use the word “frontier” let me finally return to the romantic image of advances in science which I sketched earlier. I do not believe

in it any longer. There are many frontiers and it comes down to the fact that in science one can only sometimes talk of progress. Whenever there is an advance there is a frontier, not the other way around. As to the direction of the advance, every investigator follows his own nose and does what he can. In my opinion this applies equally to space travel and to high energy physics and radio astronomy. These pursuits exist because they are possible and as long as the expense does not become too exorbitant one must, of course, continue them. But I think that one must oppose all fashion and prestige arguments. There is no natural hierarchy of problems and moreover, as Poincaré remarked long ago, a problem is never completely but always only more or less solved. [中文](#)

It seems better to me to view progress in science as the expansion of different circles of investigation, each autonomous and often apparently entirely independent of the others. The deep problems are to determine how these areas hang together, and how one can arrive at a larger unity. Biology and physical-chemical research, for example, form two such large circles. Their interrelationship seems to me to represent one of the deepest questions man can ask, a real *mysterium tremendum*. On a much smaller scale macroscopic and molecular physics form two such circles and statistical mechanics attempts to fathom their relationship. [中文](#)

(232, 449-450; 1971)

G. E. Uhlenbeck: Rockefeller University, New York.

统计力学和量子力学

乌伦贝克

《自然》杂志在这里转载了物理学家乔治·乌伦贝克在接受荷兰皇家学会授予他洛伦兹奖的仪式上发表的一篇著名演讲。乌伦贝克谈到自己长期以来一直对统计力学中的一些基本问题很感兴趣，并且提到：量子理论的基本问题在数十年内吸引了众多理论工作者，与此同时，相变（例如突发的气 - 液转换）以及相关的现象也不断引发许多尚待解决的问题。乌伦贝克还指出：那种认为科学存在大致明显的前沿（将未知领域与已知领域分开）的观点多半是一种浪漫的幻象。相反，他认为：科学中总有很多前沿，它们往往是在科学产生进展的时候才被意识到，而不是反过来。 [英文](#)

统计力学的问题真是基本性的吗？在这个问题上我自己的观点也经常改变，现在我想详细讲述一下。当我是一名年轻学生的时候，关于物质的动力学理论对我来说似乎是一种真正能够解释一些事物的理论。我花了很大工夫去钻研玻尔兹曼的《气体理论讲义》以及吉布斯的《统计力学的基本原理》。很多东西我当时并没有领会，只是在读完埃伦费斯特夫妇的那篇著名的百科全书文章（译者注：是应《数学科学百科全书》主编的要求撰写的）后才豁然开朗。那篇文章极具启发性，不仅因为清楚明了，而且因为它包括了对大师工作中一系列缺陷（超过12个）的仔细总结。这些著作就像边境站一样，可以让年轻学生了解到真正的问题所在。现在要了解这些问题是非常困难的。当前科学文献的污染使人们要花费很长时间才能找到一泓清泉，也就是那些基本概念。不仅对新学生是如此，对于任何想在自己专业之外了解一些知识的人也是一样，这一点我深有体会。 [英文](#)

尽管能成功通过多次考试，但实际上我对量子理论知之甚少，对谱

理论就更缺乏了解了。我是在1925年从罗马回来并成为埃伦费斯特的助手时，在古德斯密特的帮助下才认识到这点的。与古德斯密特的那段合作令我终生难忘，在合作中我们发现了电子的自旋，但在这里我不打算详述那段合作。古德斯密特和我经常谈起那段难忘的时光，我在这里提起它只是因为我对统计力学的观念在那段时间发生了彻底的改变。我本来认为它显然处于第二级的地位。另一方面，量子力学则提供了一个一切事物，包括气体、液体和固体的行为，必须遵循的基本原则。这似乎已被金属电子理论的成功所证实。泡利和索末菲（都是洛伦兹奖的获得者）曾揭示过所有的困难是怎样在应用了真正的量子统计之后迎刃而解的。目前还剩下几个未解之谜，如超导电性，但是我们从乐观的角度来看，最终所有难题必将得到解决。因此，我在1927年的那篇关于量子理论中统计方法的博士学位论文，便成为埃伦费斯特夫妇的百科全书文章与新的量子力学概念的一种乐观综合。未经证实的假设数目被减少到3个。

英文

之后在安阿伯市，威廉姆斯关于热噪声和散粒噪声的漂亮实验引起了我对布朗运动理论的兴趣。布朗运动理论是统计力学最好的应用之一，我觉得它非常有意思，但显然布朗运动理论并非基本性的问题。我记得非常清楚，当我和泡利谈起布朗运动理论时，他称其为“绝望物理学”。虽然我不喜欢这样的表述，但很同意泡利的观点。对于一位量子力学代的物理学家（我也属于这一代）来说，20世纪30年代的基本问题是正电子理论、量子电动力学和正在发展的核结构理论、 β 放射性理论；这些才是当务之急。

英文

在这个关键时刻，我想说：把科学进步看成是对有清楚“前沿”并能不断被“突破”的未知领域的一种征服，对我来说越来越像一个浪漫的幻象。这个图景显然是由量子力学的伟大突破激发产生的，它在很长一段时间里影响了我的判断。我甚至可以说它曾折磨着我。

英文

在1937年到1938年间我对统计力学基本特征的看法开始改变，那时候我和鲍里斯·卡恩在合伙研究所谓的凝聚理论。为什么一种气体在严格确定的临界温度之下以严格确定的密度凝聚，这个问题自范德瓦尔斯之后从未引起过人们的注意，而我们要想正确理解它似乎并不容易。在1938年范德瓦尔斯会议上与会者们对这个问题的热烈讨论中，有人甚至

怀疑统计力学的基本假设在原理上是否能够解答这个问题。这个怀疑没有根据，但是给我留下了深刻的印象。只要像液体和气体之间的平衡以及临界温度的存在这类常见现象尚未被真正理解，这个领域就还没有被征服，就不能说所有的事情都已经从原理上得到了解释，因而统计力学中还存在一些基本问题是我没有意识到的。 英文

（当我把卡恩和我所写的关于凝聚理论的文章给泡利看的时候，他看了一下说：“嗯，这个值得一读。”他确实读了，还取笑了我们文章中半吊子数学的严格性，但是我相信他理解这个问题的基本性。） 英文

战后，我继续关注量子电动力学和 β 放射性理论的新进展，并不时发表一些自己的成果。但是我的兴趣越来越偏重于统计力学中的基本问题。在20世纪50年代，我开始和我的学生也是我的朋友——已故的伯林一起撰写一部关于统计力学的书。我希望这部书能够成为那篇曾让我留下深刻印象的百科全书文章的一个现代扩充版本。我希望我们能够像埃伦费斯特夫妇那样批判性地确定理论的基础，并能够弄清楚那些仍未解决的基本问题的本质。简言之，我希望我们能够发现统计力学的“架构”。 英文

为此我们努力工作，但没有取得太大的进展，加之1962年特德·伯林突然离世，使得我们的计划能否最终实现都成了问题。但是我还是弄清了很多东西，并且感觉自己至少或多或少地理解了经典统计力学的架构。我相信一个人必须时刻记住，统计力学的任务是研究物理现象的宏观描述和微观分子描述之间的关系。这两个图景从某种意义上说是各自独立的；甚至可以说它们是在不同的层次上，因此即使定性地说也是完全不同的。如果坚持这个观点，就可以看出玻尔兹曼、吉布斯、爱因斯坦、埃伦费斯特和斯莫鲁霍夫斯基已经构造了真正的基础以供后人进一步发展。还可以看出仍然存在很多没有解决的问题，比如凝聚以及其他很多人正在研究的所谓相变过程。所有这些问题都非常艰涩，但是正如一位数学家所说的，它们是适定的，因此人们可以努力去解决它们。

英文

按照我的观点，量子力学的情況会有所不同。分子现象的经典力学

描述和量子力学描述之间的关系相当清楚，但是量子力学和宏观理论之间就另当别论了。我知道我的大部分同事都不同意这个观点。我相信最被广泛接受的观点是量子力学可以“嫁接”到玻尔兹曼和吉布斯的经典统计力学上，因此量子力学并不需要任何本质上是新的东西。以前我也这么认为，但慢慢地就不那么有信心了。最近，在液氦和超导体中发现的所谓宏观量子化以及干涉现象对我的观点影响很大。在我看来，这些发现都表明现有的超导电性和超流体性理论不能提供一个完整的解释，并且对超流体的真正宏观描述至今仍没有找到。对此我并不感到奇怪，因为量子统计力学的基础还没有被充分阐明。只要想想持续电流，就会对量子理论中遍历定理的普遍适用性产生怀疑。类似这样的问题使我感到低温物理非常有趣；它们使我精神振奋，我相信在物理学的这个“前沿”上仍有许多工作有待完成，并且还可能会有意义深刻的意外发现涌现出来。

英文

既然使用了“前沿”这个词，让我最后回头再来看看前面简要提到的科学发展的浪漫图景。我已经不再相信它了。前沿有很多，但是归根结底的事实是，在科学中一个人只能不时地谈发展。每当有了进步就会出现一个前沿，而不是反过来。至于前进的方向，每位研究者都可以按自己的主意尽力而为。在我看来，这种情况对太空旅行和对高能物理学、射电天文学都同样适用。这些研究之所以存在，是因为它们有可能实现，只要代价不是太过昂贵，当然就应该继续下去。但是我觉得应该反对所有关于时髦和地位的争论。问题并无天然的等级之分，而且正如庞加莱很久以前所指出的：一个问题永远不可能被彻底解决，只能或多或少被解决。

英文

我更愿意把科学的发展看作是向许多不同研究领域的扩展，每个领域都是自主的，而且经常表现得完全独立于其他领域。深层次的问题是确定如何使这些领域互相结合在一起，且如何达到更广泛的统一。举例来说，生物学和物理-化学研究就是两个这样的大领域。在我看来，它们之间的相互关系是人类能够提出的最有深度的问题之一，是一个真正令人敬畏的奥秘。在小得多的尺度上，宏观物理和分子物理组成了两个这样的领域，统计力学则试图去探究它们之间的关系。

英文

The Macroscopic Level of Quantum Mechanics

C. George *et al.*

Albert Einstein and other critics of quantum theory had long noted the difficulty of reconciling its description of the microscopic world—where it suggests particles often exist in a superposition of two or more states—with the existence of macroscopic objects always definite properties. Here Leon Rosenfeld and colleagues attempt to show how this inconsistency could be resolved by considering the “complementarity” of distinct modes of description at the atomic level, advocated by Niels Bohr. They argue that Bohr’s view could be put into a formal framework using the density matrix of quantum statistical mechanics. This proposal, physicists later showed, did not resolve the matter, which continues to be an important foundational problem for quantum theory today. [中文](#)

ATOMIC theory raises the epistemological problem of harmonizing the detailed dynamical description of atomic systems given by quantum mechanics and the description of individual atomic processes and of the behaviour of matter in bulk at the level of macroscopic observation. The logical side of this problem is completely elucidated by the recognition of relationships of complementarity between the two modes of description: on the one hand, there is the complementarity expressed by the indeterminacy relations, which

governs the application of the macroscopic space-time localization and momentum-energy conservation to the individual atomic processes; on the other, there is the complementarity between the account of the behaviour of a large system of atomic constituents given by quantum mechanics (and electrodynamics) and the description of the same system as a material body in terms of the concepts of macroscopic mechanics, electromagnetism and thermodynamics. [中文](#)

The formal side of the problem, however, which consists in establishing the consistency of the rules connecting the formalism of quantum mechanics with the concepts used in the account of macroscopic observation, still leaves scope for a presentation more in accordance with the conceptual simplicity of the actual situation. A general treatment of the quantum theory of large atomic systems which satisfies this desideratum has been given in a recent article¹. The purpose of this note is to outline the method and the principal results. [中文](#)

The work pursued during the past decade by the Brussels group has clearly shown that the method best adapted to the investigation of large atomic systems is not the ergodic but the kinetic approach of statistical mechanics, applied to the limiting case of infinite systems (that is, systems of infinite degree of freedom, but such that the number of elements within a given phase extension has a finite limit). Because such systems have essentially a continuous energy spectrum, the vexed question of “coarse graining” can be ignored and the asymptotic limit of the density operator for times very large on the atomic scale, but finite, can be directly discussed. This discussion leads to the conclusion² that the time evolution of the system may be split rigorously into formally independent “subdynamics”, characterized, in a manner presently to be explained, by certain projection operators depending on the correlations between the constitutive elements of the system. One of these subdynamics

belonging to the projector $\tilde{\Pi}$ given by equation (7) below contains all the information about equilibrium properties and linear transport properties. We may therefore define the macroscopic level of description of quantum mechanics as the reduced description in terms of the variables of the $\tilde{\Pi}$ -subspace. That such a reduced description is at all possible results precisely from the fact that the $\tilde{\Pi}$ -subdynamics is expressed by an independent equation of evolution. The application of this analysis to the case of a measuring apparatus, initially triggered off by an interaction of atomic duration with an atomic object, shows in a surprisingly simple way that its evolution in $\tilde{\Pi}$ -space conforms to the “reduction” rule of quantum mechanics; this important conclusion follows directly from the mathematical structure of the $\tilde{\Pi}$ -subspace of the apparatus, which entails the elimination of the initial phase relations between the components of the density operator of the atomic object. Our paper contains a simple and general derivation of these remarkable results, which shows more clearly how these methods not only lead to a deeper understanding of the epistemological problems of atomic theory, but even to a significant extension of the scope of quantum mechanics. 中文

In a superspace defined as the direct product of the Hilbert space and its dual, the density operator $\rho(t)$ appears as a supervector, varying in time according to a Liouville equation of the form

$$i \dot{\rho}(t) = L\rho(t)$$

The Liouville superoperator L may be expressed in terms of the Hamiltonian H of the system. For this purpose, we may use a convenient notation for the special class of “factorizable” superoperators $O \equiv M \times N$ depending on a pair of supervectors M, N according to the definition $O\rho = M\rho N$; we may then write $L = H \times 1 - 1 \times H$. Our aim being to find the long time effect of correlations, we must, to begin with, compare our system, defined by the Hamiltonian H , with a “model” system H_0 , from which the interaction energy V ,

responsible for the correlations, is removed, in such a way that $H = H_0 + V$. The eigenstates of H_0 form a complete orthogonal basis of representation in Hilbert space, from which we construct a similar basis in superspace: the latter may be divided into two classes of supervectors, those built up of pairs of identical (or physically equivalent) eigenstates, and those built up of pairs of different eigenstates; they belong, respectively, to two orthogonal subspaces of superspace, characterized by projection superoperators P_0, P_c . Then the projections $\rho_0 = P_0 \rho$ and $\rho_c = P_c \rho$ of the density supervector correspond, respectively, to the average distribution densities and the correlation amplitudes. Putting $L_{00} = P_0 L P_0$, $L_{0c} = P_0 L P_c$ and so on, we obtain for ρ_0 and ρ_c the coupled Liouville equations

$$i\dot{\rho}_0 = L_{00}\rho_0 + L_{0c}\rho_c, \quad i\dot{\rho}_c = L_{cc}\rho_c + L_{c0}\rho_0 \quad (1)$$

The next step is to extract from these equations the asymptotic forms $\rho_0(t)$, $\rho_c(t)$ of ρ_0 and ρ_c for large positive values of the time variable: these are expected to express our possibilities of prediction of the future evolution of the system on the macroscopic time scale.

中文

We must here restrict the generality of the Liouville superoperator in order to characterize the class of systems which we expect to exhibit the “normal” asymptotic behaviour, that is an approach to a state of equilibrium. To this end, we observe that the time evolution of the correlation density ρ_c is essentially governed by the superoperator $T_c = \exp(-iL_{cc}t)$, depending on the part of the Liouville superoperator which acts entirely in the correlation subspace. We assume accordingly that the asymptotic effect of this superoperator $T_c(t)$ upon any regular supervector A which is not an invariant is to reduce this supervector to zero: $\lim_{t \rightarrow \infty} T_c(t)A = 0$; we express by this assumption the fading of the system’s “memory” of its correlations. This condition, which may also be expressed as an analyticity condition on the Laplace transform of $T_c(t)$, has first been verified in this form by a

perturbation expansion, for infinite systems in whose description there enters a “small” physical parameter such as the coupling constant or the density³. More recently, it has been shown that for soluble models, such as the Friedrichs model, the analyticity assumption is satisfied rigorously (that is, independently of any perturbative approach) for a large class of interactions⁴. By means of this assumption, we readily derive from the second Liouville equation (1) the following relation between the asymptotic densities:

$$\tilde{\rho}_c(t) = \int_0^{\infty} d\tau e^{-iL_{cc}\tau} (-iL_{c0}) \tilde{\rho}_0(t-\tau) \quad (2)$$

It has the form of an integral equation, showing how the asymptotic correlations build up by sequences of processes starting from the average situations through which the system passes in the course of time. [中文](#)

We now introduce an asymptotic time evolution operator by writing $\tilde{\rho}_0(t)$ in the form

$$\tilde{\rho}_0(t) = e^{-i\theta t} \tilde{\rho}_0(0) \quad (3)$$

The advantage of the representation (3) is to reduce the integral equation (2) to a simple linear relation between $\tilde{\rho}_0(t)$ and $\rho_c(t)$ taken at the same time:

$$\tilde{\rho}_c(t) = C \tilde{\rho}_0(t), \quad C = C(\theta) = \int_0^{\infty} d\tau e^{-iL_{cc}\tau} (-iL_{c0}) e^{i\theta\tau} \quad (4)$$

The first Liouville equation (1) then yields a functional equation for θ :

$$\theta = L_{00} + L_{0c} C(\theta) \quad (5)$$

which can be solved by iteration. [中文](#)

The total asymptotic density $\rho = \rho_0 + \rho_c$ thus obtained has the remarkable property of being an exact solution of the Liouville equation. According to equation (4), it may be written in the form $\rho = P_a \rho$, with $P_a = P_0 + C$. It is again remarkable that this superoperator P_a has the characteristic properties of a projection operator in superspace, idempotency and “adjoint symmetry” (that is, it is such that the projection $P_a A$ of a self-adjoint supervector A is self-adjoint). The projector P_a defines a subspace in which the asymptotic density is confined. This subspace differs from the average subspace P_0 by the adjunction of a part of the correlation subspace P_c , namely that part which is specified by the superoperator C ; the latter may be interpreted as representing the building up of correlations from asymptotic average situations (we call it the superoperator of correlation creation)—it sorts out those correlation processes which have a long time effect and accordingly manifest themselves at the macroscopic level. Thus, the asymptotic density $\tilde{\rho}$ is not, as one might have expected, governed by a “kinetic equation” different from the dynamical Liouville equation: it is an exact solution of the latter, and its asymptotic character is conferred upon it by its confinement to a subspace defined by the projector P_a . 中文

The expression for the superoperator of correlation creation C , which enters in the definition of P_a , is clearly unsymmetrical in time, and gives the projector P_a the expected bias towards a preferred direction of the time evolution. In fact, time inversion transforms P_a into a different projector $\tilde{P}_a = P_0 + D$, where the superoperator

$$D = \int_0^{\infty} d\tau \, e^{i\eta\tau} (-iL_{0c}) e^{-iL_{cc}\tau}$$

is the time-inverse of C ; it contains the superoperator η which is the time-inverse of θ and obeys the equation $\eta = L_{00} + DL_{c0}$ derived from equation (5) by time-inversion. In contrast to C , the superoperator D describes sequences of “destructions” of correlations leading to

asymptotic average situations.

中文

An important element is still missing in the picture: we must establish a link between the asymptotic density supervector $\tilde{\rho}(t)$ and the arbitrarily chosen dynamical density supervector $\rho(0)$ from which the time-evolution is assumed to start. This is readily supplied, however, on the basis of a further remarkable property (easily derived) of the superoperator θ and its time-inverse η :

$$P_a \theta = L P_a, \quad \eta \bar{P}_a = \bar{P}_a L \quad (6)$$

With the notation $N_0 = 1 + DC$, it follows from equations (6) and (3) that

$$N_0 \tilde{\rho}_0(t) = N_0 e^{-i\theta t} \tilde{\rho}_0(0) = e^{-i\eta t} N_0 \tilde{\rho}_0(0)$$

and, on the other hand,

$$\bar{P}_a \rho(t) = \bar{P}_a e^{-iL t} \rho(0) = e^{-i\eta t} \bar{P}_a \rho(0)$$

This shows that $N_0 \tilde{\rho}_0(t)$ and $P_a \tilde{\rho}(t)$ have the same time-evolution, governed by the superoperator $\exp(-i\eta t)$: we may therefore equate them at any instant and in this way fix the correspondence between the dynamical and the asymptotic density. This gives the quite fundamental relation, valid at any time,

$$\tilde{\rho}(t) = \tilde{\Pi} \rho(t) \text{ with } \tilde{\Pi} = P_a N_0^{-1} \bar{P}_a \quad (7)$$

from which follows

$$\tilde{\rho}(t) = \tilde{\Sigma}(t) \rho(0) \text{ with } \tilde{\Sigma}(t) = \tilde{\Pi} e^{-iL t}$$

the answer to our last question, completing the theory.

中文

The striking feature about the superoperator $\tilde{\Pi}$ occurring in equation (7) is that it is also a projector in the extended sense defined above

(which does not include the property of self-adjointness); moreover, it is time-reversal invariant: it defines a time-symmetrical subspace of the superspace in which the asymptotic part of the time-evolution, starting from any given situation, remains confined, exhibiting the features observed at the macroscopic level; whereas the irregular fluctuations occurring on the atomic time scale are contained in the complementary subspace orthogonal to the asymptotic one. That such a clean separation between the two aspects of the atomic system could be effected is an entirely unexpected property specific to the density supervector representation: it could never have been found by a study of the evolution of the system in Hilbert space, for it can only be formulated in terms of the superspace formalism. [中文](#)

The superoperator $\tilde{\Pi}$ is not factorizable: one cannot ascribe any state vector to an asymptotic situation as we have defined it, but only a density supervector $\tilde{\rho}$. In fact, as appears from equation (4), the correlation part $\tilde{\rho}_c$ of the density ρ is directly derived from the part $\tilde{\rho}_0$ expressing the average probability distributions of the system; owing to this remarkable structure of the projector $\tilde{\Pi}$, the evolution in $\tilde{\Pi}$ -space may be entirely described in terms of probabilities only. In particular, the “reduction of the wave-packet” of an atomic system after its interaction with a measuring apparatus is a direct consequence of this property of the $\tilde{\Pi}$ -space description: the essential point being that the apparatus must necessarily belong to the macroscopic level of quantum mechanics, and that its behaviour must accordingly be described in terms of its $\tilde{\Pi}$ -space variables (loosely speaking, the behaviour of the apparatus has “thermodynamical” character, inasmuch as variables pertaining to thermodynamic equilibrium or near-equilibrium states all belong to $\tilde{\Pi}$ -space). Any phase relations in the initial state of the atomic system are therefore wiped out (that is, they are rejected into the orthogonal subspace): this is the only meaning of the “reduction” of the initial state of the atomic system resulting from the measurement. As to the human

observer, his interaction with the apparatus is also entirely described in the $\tilde{\Pi}$ -subspace, and therefore without any influence whatsoever on whatever goes on in the orthogonal subspace. [中文](#)

One further point should be mentioned. The theory gives us a simple criterion to decide whether the system shows the normal macroscopic behaviour described by thermodynamics. The superoperator of asymptotic time-evolution θ is closely related to a “collision superoperator” defined as the Laplace transform of the superoperator $L_0 c T_c(\tau) L_0$:

$$\Psi(z) = \int_0^{\infty} d\tau L_0 c T_c(\tau) L_0 e^{-z\tau}$$

Indeed, equation (5) may be written as a functional relation in terms of $\Psi(z)$:

$$i\theta = iL_{00} + \Psi(-i\theta) \tag{8}$$

Now, an homogeneous system (a system for which $L_{00} = 0$) will obviously not exhibit any tendency towards equilibrium if the collision operator vanishes identically. Equation (8) then shows that it will exhibit an irreversible tendency towards equilibrium provided that θ itself does not vanish identically. This “condition of dissipativity” is a practical one: it can be tested in concrete cases⁴ by actual computation of θ . [中文](#)

It is thus clear that the epistemological consistency problem raised at the beginning of this note is completely answered by the neat, clear-cut representation we obtain for the complementarity between the two levels of description of atomic phenomena. It need hardly be pointed out that the problem here discussed of the macroscopic level of quantum mechanics is just a simple illustration of a general method of representation in superspace, which actually amounts to an

extension of the scope of quantum mechanics. Perhaps the most significant feature of the method is the introduction of generalized projectors, involving the replacement of self-adjointness by time-inversion invariance (which reduces to the former in the absence of dissipation, that is, for systems for which the collision operator vanishes)—a generalization which may be expected to find application to a large variety of problems. [中文](#)

(240, 25-27; 1972)

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L. Rosenfeld: Nordita, Copenhagen.

Received January 28; revised March 20, 1972.

References:

1. George, C., Prigogine, I., and Rosenfeld, L., *Det kgl. Danske Videnskabernes Selskab, mat.-fys. Meddelelser*, **38**, 12 (1972).
2. Prigogine, I., George, C., and Henin, F., *Physica*, **45**, 418 (1969).
3. Balescu, R., and Brenig, L., *Physica*, **54**, 504 (1971).
4. Prigogine, I., *Non-Equilibrium Statistical Mechanics* (Interscience, 1962).
5. Grecos, A., and Prigogine, I., *Physica*, **59**, 77 (1972).
6. Grews, A., and Prigogine, I., *Proc. US Nat. Acad. Sci.*, **69**, 1629 (1972).

宏观层次的量子力学

乔治等

量子理论对微观世界的描述认为，微观粒子常常处于两个或两个以上状态的叠加态中。阿尔伯特·爱因斯坦以及其他量子理论的批评者们很早就注意到，此一对微观世界的描述与宏观物体通常具有明确的属性这一事实之间存在着难以调和的矛盾。本文中，利昂·罗森菲尔德与其同事们试图说明这一矛盾可以通过考虑尼尔斯·玻尔所倡导的、原子层次上不同描述模式间的“互补性”来加以解决。他们认为，利用量子统计力学中的密度矩阵就可将玻尔的观点纳入一个形式的框架中。物理学家们后来指出，上述提议并没有解决这个难题，直至今日它仍然是量子理论中一个重要的基本问题。 [英文](#)

原子理论提出了一个认识论问题——如何调和量子力学所给出的对原子系统的详细动力学描述，与在宏观观测水平上对单个原子过程以及大块物质行为的描述二者之间的关系。认识到两种描述模式之间的互补关系就可以完全阐明这一问题的逻辑性：一方面，不确定关系表达出互补性，它决定了宏观的时空局域性与动量-能量守恒可应用于单个的原子过程；另一方面，对于一个由原子组成的大系统，根据量子力学（和电动力学）计算其行为与将此系统视为材料实体按照宏观力学、电磁学以及热力学的概念对其进行描述，这两者之间存在着互补性。 [英文](#)

但是，这一问题形式上的一面，即建立能将量子力学公式与描述宏观观测所用概念联系起来的各个规律之间的一致性，仍为发展出一种与实际概念上的简单性更符合的表述留出了空间。我们在近期发表的一篇文章^[1]中给出的用量子理论处理较大原子体系的一般性方法能满足上述急迫需求。本文旨在概述这一方法及其重要结论。 [英文](#)

布鲁塞尔小组过去十年所从事的工作清楚地表明，最适于研究大原

子系统的是曾经用于无限系统的极限情况（即具有无穷多自由度的系统，但该系统在给定相位范围内的单元是有限的）的统计力学动力学方法而不是各态遍历方法。因为这类系统基本上具有连续能谱，所以可以忽略棘手的“粗粒化”问题。此外，关于时间的密度算符的渐近极限虽然在原子尺度上非常大，但仍然有限，可以直接讨论。讨论的结果^[2]是：或许可以将系统的时间演化严格地分成形式上独立的“子动力学”部分，以目前的解释方式（也就是采用取决于系统组成元素之间关联性的特定投影算符）来表征。下文中式（7）给出的投影算符 $\tilde{\Pi}$ 的其中一个子动力学即可包含关于平衡性质和线性输运性质的所有信息。因此，我们可以将宏观层次的量子力学描述定义为基于 $\tilde{\Pi}$ 子空间变量的约化描述。这一约化描述有可能恰好是源于以下事实： $\tilde{\Pi}$ 子动力学是由一个独立的演化方程来表示的。将这种分析方法应用于一测量装置，该装置初始时通过原子寿命与原子物体之间的相互作用而触发。结果出人意料地表明：它在 $\tilde{\Pi}$ 空间中的演化遵循量子力学的“约化”规则；这一重要结论是由该装置 $\tilde{\Pi}$ 子空间的数学结构直接得出的，它消除了原子物体密度算符各分量之间的初始相位关系。在本文中我们叙述了以一种简单而通用的方式推导出上述不寻常结论的过程，由此可以更清晰地表明：这些方法如何能不仅使我们更深刻地理解原子理论中的认识论问题，甚至还能显著拓展量子力学的范围。 [英文](#)

定义希尔伯特空间与其对偶空间的直积为超空间，其中的密度算符 $\rho(t)$ 表现为超矢量，它按照以下形式的刘维尔方程随时间变化：

$$i\dot{\rho}(t) = L\rho(t)$$

刘维尔超算符 L 可以用系统的哈密顿量 H 表示。为此，根据定义 $O\rho = M\rho N$ ，我们可以用简便的符号来表示取决于一对超矢量 M 、 N 的一类特殊的“可分解”超算符 $O \equiv M \times N$ ；然后，我们可以得到 $L = H \times 1 - 1 \times H$ 。我们的目的是要找出关联性造成的长时效应，首先我们必须将我们的由哈密顿量 H 描述的系统与由 H_0 描述的“模型”系统进行比较。在“模型”系统中，与关联性有关的相互作用能 V 被去掉，它们的关系可以由 $H = H_0 + V$ 表示。 H_0 的本征态在希尔伯特空间中形成了表象的一组完备正交基，据此，我们在超空间中构造一组类似的基矢：后者可以被分为两类超矢量——由成对的全等（或物理上等价的）本征态构成的超矢量和由成对的

不同本征态构成的超矢量；它们分别属于超空间中的两个正交子空间，可用投影超算符 P_0 和 P_c 来表征。因此，密度超矢量的投影算符 $\rho_0 = P_0 \rho$ 和 $\rho_c = P_c \rho$ 分别对应于平均分布密度和关联的振幅。取 $L_{00} = P_0 L P_0$ ， $L_{0c} = P_0 L P_c$ 等等，我们可以得到关于 ρ_0 和 ρ_c 的耦合刘维尔方程：

$$i \dot{\rho}_0 = L_{00} \rho_0 + L_{0c} \rho_c, \quad i \dot{\rho}_c = L_{cc} \rho_c + L_{c0} \rho_0 \quad (1)$$

下一步，从这些方程中求出当时间变量取很大正值时 ρ_0 和 ρ_c 的渐近形式 $\rho_0(t)$ 和 $\rho_c(t)$ ：由此我们期望能够在宏观时间尺度上预见系统未来的演变。 [英文](#)

为了表征我们期望会出现“正常”渐近行为的那一类系统，也即趋近于平衡态的系统，我们在此必须限制刘维尔超算符的通用性。为此，我们发现关联密度 ρ_c 的时间演化实质上是由超算符 $T_c = \exp(-iL_{cc}t)$ 决定的，该超算符与刘维尔超算符中在关联子空间内完全作用的那一部分有关。因此我们假定，超算符 $T_c(t)$ 对任何正则的变化超矢量 A 的渐近作用是将这个超矢量减小到零： $\lim_{t \rightarrow \infty} T(t)A = 0$ ；我们通过这个假定来表示系统对其关联性的“记忆”的衰减。这一条件也可表示为对 $T_c(t)$ 进行拉普拉斯变换的解析条件。在那些可以引入一个诸如耦合常数或密度等“小”物理参数来表示的无限系统中，利用微扰展开，人们已经首次证实该条件确实是这样的形式^[3]。最近有人指出：对于可解模型，例如弗里德里克斯模型，有一大类相互作用是严格满足解析性假定的（即独立于任何微扰方法）^[4]。根据上述假设，我们很容易从刘维尔方程（1）中的第二个式子导出渐近密度之间的下述关系：

$$\tilde{\rho}_c(t) = \int_0^\infty d\tau e^{-iL_{cc}\tau} (-i L_{c0}) \tilde{\rho}_0(t-\tau) \quad (2)$$

上式具有积分方程的形式，由此可以说明系统的渐近关系是怎样通过以系统在一段时间内的平均状态为起始的一系列过程而建立的。 [英文](#)

现在我们通过 $\tilde{\rho}_0(t)$ 的下述表达式来引入渐近时间演化算符：

$$\tilde{\rho}_0(t) = e^{-i\theta t} \tilde{\rho}_0(0) \quad (3)$$

表达式 (3) 的优点是可将积分方程 (2) 简化为时间取相同值时与 $\rho_c(t)$ 之间的一种简单线性关系：

$$\tilde{\rho}_c(t) = C \tilde{\rho}_0(t), C = C(\theta) = \int_0^\infty d\tau e^{-iL_{cc}\tau} (-iL_{c0}) e^{i\theta\tau} \quad (4)$$

因此，由刘维尔方程 (1) 中的第一个式子可以得到一个关于 θ 的函数方程：

$$\theta = L_{00} + L_{0c} C(\theta) \quad (5)$$

该式可用迭代法求解。 [英文](#)

由此得到的总渐近密度 $\rho = \rho_0 + \rho_c$ 具有不同寻常的性质——它是刘维尔方程的一个精确解。根据式 (4)，可以将其改写成 $\rho = P_a \rho$ 的形式，其中 $P_a = P_0 + C$ 。超算符 P_a 在超空间中具有投影算符的特性、幂等性和“伴随对称性”（即，自伴超矢量 A 的投影 $P_a A$ 也是自伴的），这些同样不同寻常。投影算符 P_a 定义了一个渐近密度有限的子空间。这个子空间与平均子空间 P_0 之间的差别在于叠加了关联子空间 P_c 的一部分，即由超算符 C 确定的那部分；可以把后者解释为代表了在渐近平均情况下的关联建立（我们称之为关联产生超算符）——它可以区分出那些具有长时效应并因此在宏观层次上有所显现的关联过程。因此，渐近密度 $\tilde{\rho}$ 并非如预期的那样，是由不同于刘维尔动力学方程的“动力学方程”决定的：它是刘维尔动力学方程的一个精确解，其渐近特性是通过被限制在由投影算符 P_a 定义的子空间中而得到的。 [英文](#)

在 P_a 的定义中引入了由关联产生的超算符 C 的表达式，该表达式在时间上显然是非对称的，它使投影算符 P_a 向时间演化的择优方向发生了预期的偏移。实际上，时间反演将 P_a 变换成了另一个投影算符 $\tilde{P}_a = P_0 + D$ ，其中超算符

$$D = \int_0^\infty d\tau e^{i\eta\tau} (-iL_{0c}) e^{-iL_{cc}\tau}$$

是 C 的时间逆；它含有 θ 的时间逆——超算符 η ，并且满足将式 (5) 进行

时间反演而推导出的表达式 $\eta = L_{00} + DL_{c0}$ 。与 C 不同，超算符 D 描述的是导致出现渐近平均状态的关联“相消”序列。 英文

在此图景中仍然缺少了一个重要的元素：我们必须在渐近密度超矢量 $\tilde{\rho}(t)$ 与任意选取的动态密度超矢量 $\rho(0)$ 之间建立起联系，其中 $\rho(0)$ 被假定为时间演化的起始点。这一点很容易实现，但要以超算符 θ 及其时间逆 η 的一个更为不同寻常的性质（容易推导出）为基础：

$$P_a \theta = L P_a, \quad \eta \bar{P}_a = \bar{P}_a L \quad (6)$$

记 $N_0 = 1 + DC$ ，由式（6）和式（3）可得：

$$N_0 \tilde{\rho}_0(t) = N_0 e^{-i\theta t} \tilde{\rho}_0(0) = e^{-i\eta t} N_0 \tilde{\rho}_0(0)$$

而另一方面：

$$\bar{P}_a \rho(t) = \bar{P}_a e^{-iL t} \rho(0) = e^{-i\eta t} \bar{P}_a \rho(0)$$

这表明 $N_0 \tilde{\rho}_0(t)$ 和 $\bar{P}_a \tilde{\rho}(t)$ 的时间演化相同，均由超算符 $\exp(-i\eta t)$ 决定：因此，我们可在任意时刻令二者相等，由此得到动态密度与渐近密度之间的对应关系。这样就给出了一个非常基本的关系，并且在任意时刻均成立：

$$\tilde{\rho}(t) = \tilde{\Pi} \rho(t) \quad \text{式中} \quad \tilde{\Pi} = P_a N_0^{-1} \bar{P}_a \quad (7)$$

由此可得：

$$\tilde{\rho}(t) = \tilde{\Sigma}(t) \rho(0) \quad \text{式中} \quad \tilde{\Sigma}(t) = \tilde{\Pi} e^{-iL t}$$

这就是最后一个问题的答案，整个理论完成。 英文

式（7）中超算符 $\tilde{\Pi}$ 的显著特征是：根据上文中的定义，它也是一个意义扩展了（不包含自伴性质）的投影算符；此外，它在时间反演后保持不变：它定义了超空间中的一个时间对称的子空间，从任意给定的状态开始，该子空间中时间演化的渐近部分保持有限，表现出了在宏观尺度上所观测到的性质；而在原子时间尺度上出现的不规则涨落则被纳入与渐近子空间正交的互补子空间中。对于密度超矢量表象而言，能够

实现原子系统两个方面之间的明确分离完全是一个出乎意料特性：在希尔伯特空间中对系统演化进行研究是不可能得到这一结果的，因为只有通过超空间的形式才能阐释它。 [英文](#)

超算符 $\tilde{\Pi}$ 是不可分解的：除密度超矢量 $\tilde{\rho}$ 外，不能将其他任何态矢量归于我们所定义的渐近状态。事实上，由式（4）可以看出：密度 ρ 的关联部分 $\tilde{\rho}_c$ 是从表征系统平均概率分布的 $\tilde{\rho}_0$ 部分直接推导出来的；由于投影算符 $\tilde{\Pi}$ 的这种特殊结构，有可能仅用概率就能完全描述 $\tilde{\Pi}$ 空间中的演化。特别地，原子系统与测量装置发生相互作用之后的“波包坍塌”正是 $\tilde{\Pi}$ 空间描述的这一性质的直接结果：最关键的一点是，测量装置必须属于量子力学的宏观层次，于是它的行为必须通过它在 $\tilde{\Pi}$ 空间中的变量来描述（大体来说，因为与热力学平衡态或近平衡态有关的变量都属于 $\tilde{\Pi}$ 空间，所以测量装置的行为具有“热力学”的特征）。因此，我们可以去掉原子系统初态中的所有相位关系（即，使它们退化到正交子空间）：这就是原子系统的初态经测量后“坍塌”的唯一内涵。至于人类观测者，他与装置之间的相互作用也在 $\tilde{\Pi}$ 子空间中得到了完整的描述，因而他对正交子空间中发生的一切不会造成任何影响。 [英文](#)

另有一点值得一提。上述理论给我们提供了一条简单的标准，用以判断系统是否表现出由热力学所描述的标准宏观行为。渐近时间演化超算符 θ 与由超算符 $L_0 c T_c(\tau) = L_{c0}$ 的拉普拉斯变换而定义的“碰撞超算符”之间有密切的关系：

$$\Psi(z) = \int_0^{\infty} d\tau L_{0c} T_c(\tau) L_{c0} e^{-z\tau}$$

实际上，式（5）可改写成含有 $\Psi(z)$ 的泛函关系式：

$$i\theta = iL_{00} + \Psi(-i\theta) \quad (8)$$

于是，当碰撞算符为零时，一个均匀系统（ $L_{00} = 0$ 的系统）显然不会有任何趋于平衡的表现。由式（8）可知：如果 θ 本身没有同时趋于零，则系统将不可逆地趋向平衡。这种“耗散条件”是实际存在的：在具体情况下^[4]，通过实际计算 θ 值可验证这一点。 [英文](#)

由此可见，我们为得到对原子现象两种层次描述之间的互补性而采用的这种简洁、明晰的表象彻底解决了本文开篇处提出的认识论一致性的问题。不言自明的是，此处讨论的宏观层次量子力学问题仅仅是超空间表象这一通用方法的一个简单演示，它实际上拓展了量子力学的范畴。上述方法最为重要的特征或许是引入了广义投影算符，包含用时间反演不变性替换自伴性（对于碰撞算符为零的系统，在无耗散时前者可约化为后者）——可以预期这种推广将在大量问题中得到应用。 英文

（沈乃澍 黄尧 翻译；李军刚 审稿）

Computer Analyses of Gravitational Radiation Detector Coincidences

J. Weber

Within the context of general relativity, gravitational radiation is expected to come from massive and compact objects such as neutron stars and black holes. Joseph Weber designed and built two antenna systems for detecting gravitational radiation, separated by about 1,000 km. Here he analyses signals obtained from them, and finds coincidences in detection that he interprets as evidence for gravitational waves passing through the instruments. The claim is now known to be wrong, but the paper helped to launch the field of gravitational-wave detection. Indirect evidence for gravitational radiation was later seen in observations of the orbit of a millisecond pulsar, but a direct detection remains to be achieved. [中文](#)

MY earlier publications¹ have reported the concept, theory, and development of an antenna to detect gravitational radiation. These antennae are well isolated from the local environment by acoustic and electromagnetic shielding but they do respond to sufficiently large local disturbances. Effects of the local environments can, however, be minimized when two detectors are used which are a considerable distance apart. For this reason coincidence experiments at 1,661 Hz

were carried out with two antennae, one situated at the University of Maryland and the other 1,000 km away at the Argonne National Laboratory. [中文](#)

For all experiments reported here the only coincidences which were recorded were those which occurred within a predetermined time Δt .

[中文](#)

Coincidences may be due to excitation of both detectors by a common source or to chance. It is customary to compute the chance (accidental) coincidence rate by formulating a classification scheme for the coincidences and computing the number of chance coincidences in each class. A significant excess of detected event over the chance coincidence rate for a given class establishes with a certain level of confidence that not all coincidences are due to chance. [中文](#)

[文](#)

For two years the experiments were done as follows. The outputs of the Maryland and Argonne detectors are obtained from synchronous detectors which have free running crystal reference oscillators and twin channels with the reference shifted by $\pi/2$ in one of them. The two channel outputs are squared and summed to recover the power, with a time constant of 0.5 s. The envelope of the total power output of the Argonne detector was transmitted over a telephone line to Maryland, in coded digital form, and reconverted to analogue d.c. at Maryland. The outputs are fed to a coincidence detector. If both channels cross some preset threshold from below, within the time interval Δt , a pulse is emitted to drive a recorder marker pen. [中文](#)

The amplitudes of the noise pulses have a Rayleigh distribution, and their shapes vary widely. Analysis is simplified if all pulses have roughly the same shape, because then one parameter, the pulse height, will suffice for their classification. To shape the pulses properly a second stage of filtering is carried out after coincidence

detection. There is a small amount of additional filtering associated with the mass of the pen which records the output on a chart. 中文

文

A mean solar day is chosen as the unit of time. Consider a given coincidence with power amplitudes P_A and P_B for the two channels. Let N_A and N_B represent the number of times per day that the powers P_A and P_B are equalled or exceeded, on the average. Let Δt be the maximum time between threshold crossings for the two channels in order to record a coincidence. The expected number of chance coincidences with amplitudes equal to or exceeding those observed for an experiment with effective duration M days is η_{AB} with

$$\eta_{AB} = 2N_A N_B \Delta t M$$

(1)

To employ equation (1) we select some arbitrary numbers which may or may not be the same for channels A and B . A given class consists of all those coincidences for which N_A and N_B each are equal to or less than the arbitrarily selected numbers for them. 中文

A second classification scheme was employed in order to determine if the difference between the observed and chance coincidences is sensitive to details of the statistical methods. Instead of requiring N_A and N_B each to remain within certain bounds for a given class, we require the product $N_A N_B$ to be equal to or less than some arbitrary number for a given class. The total number of such chance coincidences will be finite because neither N_A nor N_B can ever be less than one or greater than the total number of pulses observed for each channel. The most useful classifications are those for which N_A and N_B are less than some number N_S which is about an order greater than the numbers which characterize most of the real coincidences classified by equation (1). 中文

A two dimensional space with N_A and N_B as coordinates is useful to calculate the number of chance coincidences $\tilde{\eta}_{AB}$ for which the product $N_A N_B$ is equal to or smaller than some constant and for which neither N_A nor N_B exceeds some maximum value N_S . $\tilde{\eta}_{AB}$ is expression (1) plus the integral under the hyperbola $N_A N_B = \text{constant}$, that is

$$\tilde{\eta}_{AB} = 2N_A N_B \Delta L M [1 + \ln(N_S^2 / N_A N_B)] \quad (2)$$

中文

In equations (1) and (2) M is smaller than the actual number of days which the experiments run, because allowance must be made for the detector relaxation time after crossing the threshold. A new coincidence cannot occur during this time. 中文

Early experiments^{5,6} observed that the number of coincidences for certain values of N_A , N_B , $N_A N_B$ substantially exceeded the accidental rate computed from equations (1) and (2). These gave about the same numbers for the difference of the observed and chance coincidences. The conclusion that positive results are obtained is based on certain assumptions—for example that the classification scheme based on amplitude alone with the successive filtering is sound. To test this, a parallel experiment was done to measure the accidental rate by inserting time delays of varying length in one channel or the other.

中文

This time delay experiment showed a large decrease in the number of coincidences for which $N_A, N_B \leq 100$; and also those coincidences for which $N_A N_B \leq 6,000$ with $N_S \leq 1,000$ for all time delays significantly larger than Δt . There is a subjective element in the data processing, in that for each coincidence mark the leading edge of the pulse must be examined. If it increases smoothly to a peak then the peak value is the required amplitude. If there is a discontinuity in slope before reaching

the peak it is concluded that the excitation which results in a threshold crossing was followed at the discontinuity by a heat bath noise excitation. The required pulse height is then only the value measured to the point of discontinuity. Sometimes the discontinuity is not well defined and a human decision is needed. 中文

Using a magnetic tape and a computer provides an independent procedure for data processing. The human element is only involved in the program preparation. A variety of thresholds and time delays can be applied to any stretch of data. The synchronous detector output with 0.5 s filter time constant was recorded in digital form every 0.1 s with both channels on one tape. A computer program was prepared by Mr. Brian K. Reid in the following way: thresholds were set such that if both channels crossed from below within 0.5 s the computer measured the pulse heights after a second stage of 5 s time constant filtering and a third stage of filtering with 0.5 s time constant to simulate the ink recorder pen. Then the computer counted the number of times the filtered data amplitude was equalled or exceeded for the previous hour, the previous 6 h, and the given day following the schematic diagram in Fig. 2. The same procedure was repeated for time delays of 1 s, 2 s, 5 s, 10 s, 20 s and 40 s. 中文

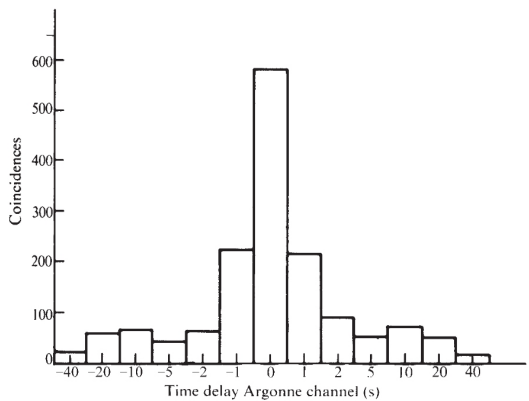


Fig. 1. Computer analyses of magnetic tapes, October 1970–February 1971. 中文

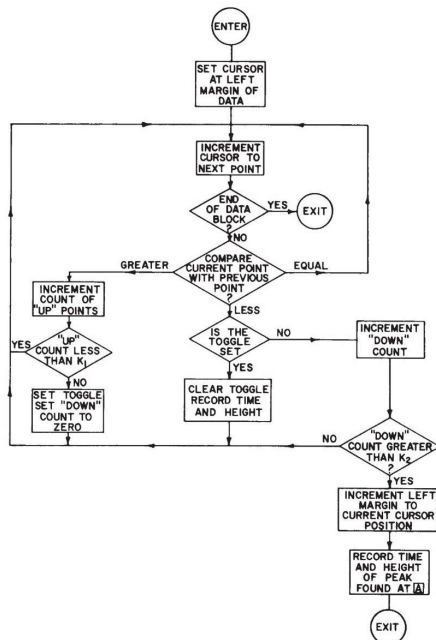


Fig. 2. Computer program for statistics of coincidences recorded on magnetic tape.

中文

The program was inaccurate beyond 20 s delay and the bin values given in Fig. 1 for 40 s delay are much too small. A subsequent computer program has verified that there is no further decrease in the chance coincidence rate for delays exceeding 100 times the coincidence window.

中文

The pen and ink records show pulses with relatively smooth leading edges. The greater time resolution of magnetic tape results in pulses with a certain roughness everywhere. It is therefore difficult to prepare a program which measures the pulse height to a point of discontinuity in leading edge slope. The computer defines the peak as the point where a trend of increases is followed by a trend of decreases. Detailed study of greatly expanded pulses indicates that this is a sound procedure for most of the coincidences. Because of the 5 s averaging it is expected that the pulse peak will be reached between 2 and 15 s after the threshold is crossed and only those coincidences are recorded which reach peaks within such an interval. This range of values is required because of noise and the initial conditions of charge

on the capacitors of the filter. The computer measures the area of the pulse, but this is not included in the statistical analysis. [中文](#)

A small fraction of the coincidences are not found by the program because no peak is found in the required interval following threshold crossing. Detailed plotting usually permits the peak to be identified within the required time after threshold crossing. Such coincidences are not included in these data in order to conserve computing time and costs. [中文](#)

Results are shown in Fig. 1 for all coincidences for which $N_A N_B \leq 10,000$ and $N_S \leq 1,000$. The low intensity coincidences are often counted more than once if threshold is crossed and re-crossed in the presence of noise. The histogram therefore shows about twice the real number of coincidences for the 120 day period covered by the tapes. All data of Fig. 1 came from the computer and not from human examination of printed lists. [中文](#)

It is significant that for delays in either channel as small as twice the coincidence interval Δt , the coincidence rate drops by a factor about 2.5. At delays of 20 s the coincidence rate is down by roughly a factor 10. These data, untouched by human hands, leave no doubt whatsoever that the gravitational radiation detectors, separated by 1,000 km, are being excited by a common source. [中文](#)

Before we can conclude from Fig. 1 that the source is gravitational radiation, it is essential to rule out other presently known interactions including seismic, electromagnetic, and cosmic ray effects. [中文](#)

The detectors are coupled to each other by the Earth and respond to sufficiently large seismic events. A number of seismometers were developed including a vertical axis accelerometer tuned to the detector frequency of 1,661 Hz, a three axis accelerometer covering frequencies near 100 Hz, and a two axis tilt meter. No significant correlations were observed between seismic activity and the

coincidences. [中文](#)

Electromagnetic signals may enter the instrumentation through the vacuum chambers and through the cables and shields of the electronic equipment. Experiments were carried out to measure the susceptibility to electromagnetic excitation. It was found that 1,661 Hz magnetic fields of amplitude about 0.1 Gauss will excite the detector, and much larger fields at 830.5 Hz will also excite the detector. Non-linear effects are expected because the electromagnetic stress tensor is quadratic in the fields, and electromagnetic stresses can cause mechanical forces on the detector cylinders. The response is large at 1,661 Hz because the electronics has its acceptance band there and because 1,661 Hz currents in the aluminium cylinder give forces by interacting with the Earth's magnetic field. [中文](#)

Both laboratory sites are to some degree shielded as a result of grounded metal ceilings and structures around the apparatus. A radio receiver was employed at the Maryland site, with non-linear pre-amplifier and post-amplifier tuned to a narrow band of frequencies near 1,661 Hz. The receiver sensitivity could be adjusted to respond to fields much smaller than those which excite the gravitational radiation detectors. Magnetic and electric dipole antennae were employed at different locations and with different orientations at various times. Local electromagnetic fields associated with air conditioning, magnetic tape recorders, and power line fluctuations limited the radio receiver sensitivity to values about three orders smaller than those to which the gravitational radiation detector responds. No significant correlations were observed with the gravitational radiation detector coincidences. [中文](#)

There is additional evidence that the coincidences are not due to electromagnetic or seismic interactions. The gravitational radiation detector system input temperature has been measured by a noise generator. This resulted in an accurate accounting of all significant

signal sources and ruled out the possibility that any significant fraction of the input temperature is due to some background other than internal noise. If the coincidences are caused by terrestrial effects such as seismic and electromagnetic activity, these must give signals arriving simultaneously or nearly simultaneously at both sites from a region on or within the Earth. For each coincident arrival at the two locations, however, there must be many individual arrivals, and these would result in a higher system noise level than is observed. Measurements were also carried out of coincidence rates for a pair of gravitational radiation detectors at the Maryland site over a period of six months. Within limits of experimental error the one-site, two-detector coincidence rate was identical with the separated-site two-detector coincidence rate. This indicates that for the sensitivities reported here, the isolation from the local environments was adequate and that electromagnetic and seismic interactions do not cause the observed coincidences. [中文](#)

The separation of 1,000 km makes a cosmic ray shower explanation very unlikely. Nonetheless it was important to investigate the effect of cosmic ray charged particles. Professors N. Sanders Wall and Gaurang B. Yodh and Dr. David Ezrow instrumented one of the Maryland site gravitational radiation detectors with Čerenkov radiation counters and later with meter square plastic scintillators. They observed no significant correlations with the gravitational radiation detector coincidences⁷. [中文](#)

A search was made for coincidences between a 1,661 Hz gravitational radiation detector and a 5,000 Hz mode of a second gravitational radiation detector, both at the Maryland site. No excess of coincidences above the chance rate was observed. Subsequent investigation showed that the 5,000 Hz mode was a bending mode and not a compressional mode. General relativity theory predicts that this bending mode should not interact with gravitational radiation.

The lack of coincidences is thus evidence against a non-gravitational radiation origin for the 1,661 Hz coincidences. 中文

Other papers have presented evidence that there is anisotropy of the observed coincidences, the maxima occurring in the direction of the galactic centre⁸. Experiments with a disk were consistent with predictions of Einstein's pure tensor theory. Small effects of the local environment can affect the anisotropy in a significant way. To average these properly at least six months of data are required. The magnetic tapes considered here did not have times continuously written. Gaps and recorder failures left insufficient data for a study of the anisotropy. Visual examination of the lists of coincidences found by the computer implied that the data are consistent with the earlier anisotropy experiments based on human observer study of pen and ink recorder charts. 中文

The present data are free of human observer bias. No assumptions are made concerning the duration of expected pulses or their shapes beyond the requirement of a fairly smooth leading edge. This is important because addition of noise will change the shape of received pulses. It is considered established beyond reasonable doubt that the gravitational radiation detectors at ends of a 1,000 km baseline are being excited by a common source as a result of interactions which are neither seismic, electromagnetic nor those of charged particles of cosmic rays. 中文

I thank F. J. Dyson, V. Trimble, and G. R. Ringo for valuable discussions and D. J. Gretz and J. Peregrin for maintaining and operating the gravitational radiation detectors. This work was supported in part by NSF and in part by the Computer Science Center of the University of Maryland. 中文

(240, 28-30; 1972)

Maryland.

Received April 19; revised August 4, 1972.

References:

1. Weber, J., *Phys. Rev.*, **117**, 306 (1960).
2. Weber, J., in *General Relativity and Gravitational Waves*, chap. 8 (Interscience, New York, London, 1961).
3. Weber, J., in *Relativity Groups and Topology*, 875 (Gordon and Breach, New York, 1964).
4. Weber, J., *Nuovo Cim. Lett.*, Series I, **4**, 653 (1971).
5. Weber, J., *Phys. Rev. Lett.*, **22**, 1320 (1969).
6. Weber, J., *Phys. Rev. Lett.*, **24**, 276 (1970).
7. Ezrow, D., Wall, N. S., Weber, J., and Yodh, G. B., *Phys. Rev. Lett.*, **24**, 17 (1970).
8. Weber, J., *Phys. Rev. Lett.*, **25**, 180 (1970).
9. Weber, J., *Nuovo Cim.*, **4B**, 197 (1971).

引力辐射探测器符合计数的计算机分析

韦伯

广义相对论认为引力辐射来自大而重的致密物体，如中子星和黑洞。约瑟夫·韦伯设计并搭建了相距约1,000千米的两个天线系统来探测引力辐射。在这篇文章中，他分析了由这些天线系统得到的信号，并在探测中发现了符合事件，他认为这些符合事件是引力波穿过实验装置的证据。现在我们知道他的这种论断是错误的，但是这篇论文帮助人们开创了引力波探测的领域。之后，人们在对一个毫秒脉冲星轨道的观测中发现了引力辐射的间接证据，但直接探测还有待实现。 [英文](#)

我已经在之前发表的文章^[1]中陈述过探测引力辐射的天线的概念、理论和研制。这些天线通过声屏蔽和电磁屏蔽与局部环境充分隔离，但仍然会对足够大的局部扰动产生响应。不过，使用相距很远的两个探测器可以将局部环境的影响降到最低。因此我们使用两个天线在1,661赫兹频率上进行了符合计数实验，其中一个天线位于马里兰大学，另一个则位于1,000千米之外的阿贡国家实验室。 [英文](#)

在本文报告的所有实验中，被记录的符合事件都发生在事先确定的时间间隔 Δt 中。 [英文](#)

符合事件可能是因为一个共同的源激发两个探测器而引起的，也可能是偶然产生的。制定一个符合事件的分级方案并计算每个等级中的偶然符合数目，是计算偶然符合计数率的通常做法。对一个给定等级来说，如果探测到的符合事件明显超出该等级的偶然符合计数率，就表明在一定置信水平上，并非所有的符合计数都是偶然产生的。 [英文](#)

两年时间的实验开展情况如下。马里兰和阿贡探测器的输出由同步探测器获得，该同步探测器装备了自由运转的晶体参考振荡器，并具有双通道，其中一个的参考相位移动了 $\pi/2$ 。设定时间常数为0.5秒，可将两个通道的输出求平方和来得到原先的功率。通过电话线将阿贡探测器的总功率输出包络以数字编码形式传递到马里兰，并在马里兰将其转换回模拟直流信号。输出信号由一个符合探测器接收。在时间间隔 Δt 内，如果两个通道的信号都上升至超过事先设定的阈值，就会发出一个脉冲来驱动记录仪的记号笔。

英文

噪声脉冲的幅值符合瑞利分布，且其形状变化很大。如果所有脉冲的形状都大致相同，分析将得以简化，因为这时只需使用脉冲高度这一个参数就能够对它们进行分级。对脉冲的适当整形需要在符合计数检测后再进行第二级过滤。此外还存在少量附加滤波，它们与在图纸上记录输出的记号笔的质量有关。

英文

选择平均太阳日作为时间单位。考虑功率幅值分别为 P_A 和 P_B 的两个通道的给定符合计数。令 N_A 和 N_B 代表每天功率值达到或者超过 P_A 和 P_B 的平均次数， Δt 代表：为了记录到一次符合计数，两个通道越过功率阈值的最大时间间隔。在有效实验时间 M 天的观测中，功率幅值达到或者超过规定值的偶然符合的预期次数 η_{AB} 为：

$$\eta_{AB} = 2N_A N_B \Delta t M$$

(1)

为了利用公式(1)，我们任意选择了一些数值，这些数值对通道A和B来说可能相同，也可能不相同。一个给定的等级包含所有满足下述条件的符合计数，即 N_A 和 N_B 都等于或者小于那些针对它们任意选择的数值。

英文

为了确定观测到的符合计数和偶然符合计数的差值是否对统计方法的细节敏感，我们采用了另一种分级方案。我们不限定 N_A 和 N_B 每一个都必须处在给定的等级区间中，而是要求它们的乘积 $N_A N_B$ 等于或者小于为某一给定等级设定的任意值。因为不管是 N_A 还是 N_B 都不能小于1，也不能大于在每个通道观测到的总脉冲数量，所以这样的偶然符合的总数目

是有限的。最有用的等级是那些 N_A 和 N_B 小于某个数值 N_S 的，这个 N_S 比按照公式（1）进行分级的大多数代表真正符合计数的数目约大一个数量级。 [英文](#)

考虑一个以 N_A 和 N_B 为坐标的二维空间，它有助于计算乘积 $N_A N_B$ 等于或者小于某个常数并且 N_A 和 N_B 都不超过某个最大值 N_S 的偶然符合的数目 $\tilde{\eta}_{AB}$ 。 $\tilde{\eta}_{AB}$ 等于公式（1）加上双曲线 $N_A N_B = \text{常数}$ 下的积分，即

$$\tilde{\eta}_{AB} = 2N_A N_B \Delta t M [1 + \ln(N_S^2 / N_A N_B)] \quad (2)$$

[英文](#)

公式（1）和（2）中的 M 小于实验运行的实际天数，这是因为必须考虑越过阈值后探测器的弛豫时间，在这段时间内不会出现新的符合计数。 [英文](#)

由早期的一些实验^[5,6]发现：对于特定的 N_A 、 N_B 、 $N_A N_B$ 值，符合计数的数目大大超过了由公式（1）和（2）计算得到的偶然符合计数率。这些实验给出的符合计数观测值和偶然符合计数的差值大致相同。认为能够获得肯定性结果的结论建立在某些假设的基础之上——例如，假设单纯基于幅值然后再过滤的分级方案是合理的。为了检验这个假设，我们进行了一项对照实验，通过在一个或者另一个通道中加入不同长度的时间延迟来测量偶然符合计数率。 [英文](#)

这个时间延迟实验显示，在时间延迟显著大于 Δt 的情况下：当 N_A 、 $N_B \leq 100$ 时，符合计数的数目大大降低；当 $N_A N_B \leq 6,000$ 且 $N_S \leq 1,000$ 时，符合计数的数目也大大降低。数据处理中的一个主观因素在于，标记每个符合计数时都必须检查脉冲的前沿。如果它平滑地上升到峰顶，那么这个峰值就是所需的幅值。如果在到达峰顶前的上坡中间有一个间断点，我们就认为：导致超越阈值的激发之后，在间断点处紧跟着一个热库噪声激发。这样所需的脉冲高度就只能是间断点处的值。有时候这个间断不是很明显，需要人为主观判断。 [英文](#)

磁带和计算机的应用提供了一个独立的数据处理程序。只有在程序准备的过程中会牵涉到人为因素。可以对任何一部分数据应用不同的阈

值和时间延迟。设过滤时间常数为0.5秒，同步探测器两个通道的输出都以数字形式每隔0.1秒记录到同一个磁带上。布赖恩·里德先生准备了一个计算机程序，情况如下：设定好阈值，一旦两个通道在0.5秒的时间范围内都上升超过阈值，计算机就会在第二级时间常数为5秒的过滤以及第三级时间常数为0.5秒的过滤之后模仿记录笔来测量脉冲高度。接下来计算机按照图2所示的流程计算出前1小时、前6小时以及某一天之内过滤后的数据幅值达到或者超过阈值的次数。对1秒、2秒、5秒、10秒、20秒和40秒的时间延迟，也重复运行同样的程序。

英文

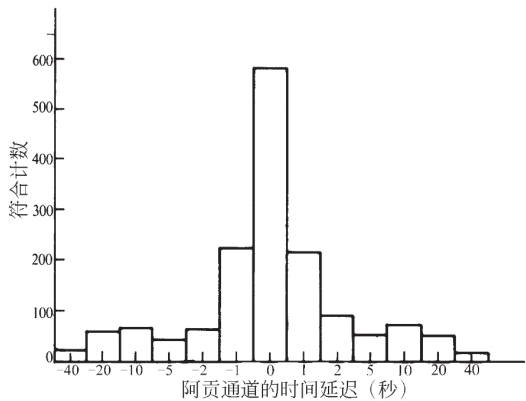


图1．磁带数据的计算机分析，1970年10月至1971年2月

英文

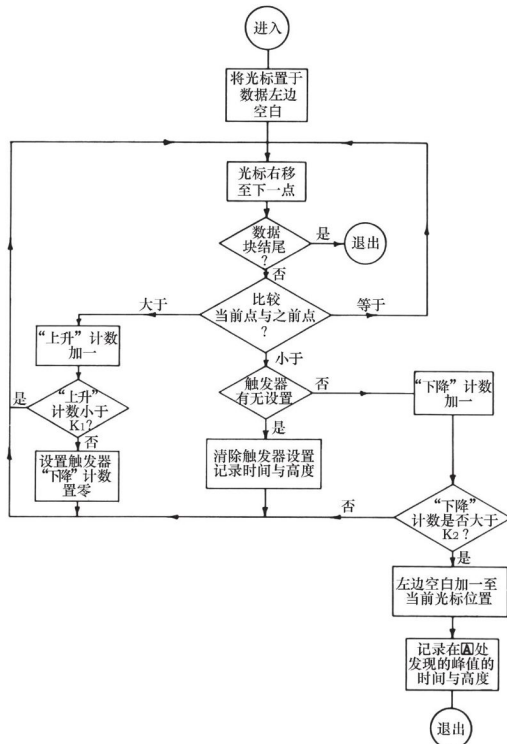


图2. 用于对磁带上记录的符合计数进行统计的计算机程序 英文

这个程序对20秒以上的延迟不是很精确。图1中40秒延迟的柱高的数值太小了。随后的一个计算机程序证实：对于超过符合时间窗100倍以上的延迟，偶然符合计数率并没有进一步的降低。 英文

笔墨记录的脉冲前沿比较平滑。磁带记录的时间分辨率较高，导致脉冲在各点处都有点粗糙。因此很难用一个程序去测量到前沿上坡间断点处的脉冲高度。计算机对峰顶的定义是从上升走向变为下降走向的转折点。对大大扩展的脉冲进行的详细研究显示：对绝大多数符合计数，这一定义是合理的。由于平均时间为5秒，一般预期在超越阈值后2秒到15秒之间达到脉冲峰顶，也只有当峰顶出现在这一区间时，符合才会被记录。规定这一数值范围是因为考虑到了噪声和滤波电路的电容器的初始充电情况。计算机也测量脉冲的面积，不过没有包括在统计分析中。

英文

由于在超越阈值后所要求的时间区间内未能发现峰顶，有一小部分符合计数没有被程序捕捉到。一般来说，通过详细的测绘可在超越阈值

后所要求的时间内识别出这个峰顶。为了节约计算时间和成本，这样的符合计数没有被包括在这些数据中。 [英文](#)

图1是 $N_A N_B \leq 10,000$ 且 $N_S \leq 1,000$ 的所有符合计数结果。当阈值被超越且由于噪声的存在而被再次超越时，低强度的符合经常被多次计数。因此，直方图给出的符合计数是磁带记录的120天内真实符合计数的两左右。图1中所有数据都来源于计算机，而不是对打印列表人工检验的结果。 [英文](#)

值得注意的是：任一通道的时间延迟，尽管小到只有符合计数时间间隔 Δt 的两倍，也使得符合计数率下降到原来的2/5。对20秒的延迟，符合计数率下降到原来的1/10左右。这些未经人工处理的数据毫无疑问地表明，相隔1,000千米的引力辐射探测器受到了同一个源的激发。

[英文](#)

在我们根据图1确定这个源就是引力辐射之前，必须排除其他目前已知的干扰。这些干扰包括地震、电磁以及宇宙线的影响。 [英文](#)

这些探测器通过地球互相耦合，会对足够大的地震事件产生响应。我们研制了许多台地震计，包括一台探测器频率被调到1,661赫兹的垂直轴加速度计、一台覆盖100赫兹左右频率的三轴加速度计以及一台二轴倾斜仪。在地震活动与符合计数之间没有发现显著的关联。 [英文](#)

电磁信号可能会通过真空室或者电子设备的电缆及屏蔽物进入仪器。我们进行了一些实验来测量系统对电磁干扰的敏感度。结果发现强度约为0.1高斯的1,661赫兹磁场能够激发探测器。若为830.5赫兹，则要激发探测器所需的磁感应强度就要大得多。因为电磁应力张量是电磁场的二次型，并且电磁应力可以在探测器圆筒上产生机械力，所以这种非线性效应是可以预期的。1,661赫兹处的响应很强是因为电子在那里有一个接收带，并且因为在铝制圆筒中1,661赫兹的电流通过与地磁场的相互作用而产生了力。 [英文](#)

由于金属天花板和仪器周围的金属结构接地，两个实验站在某种程度上都是被屏蔽的。我们在马里兰站使用了一台无线电接收器，将其非线性前置放大器和后置放大器调频到1,661赫兹附近的窄波段。接收器

的灵敏度可调，哪怕场强小到远远不够激发引力辐射探测器，也可以产生响应。我们在不同的位置使用磁偶极和电偶极天线，在不同的时间采用了不同的方向。与空调、磁带记录仪和电源线波动相关的局部电磁场限制了无线电接收器的灵敏度，其数值大概比引力辐射探测器响应的小3个数量级。在电磁干扰与引力辐射探测器符合计数之间没有观测到显著关联。 [英文](#)

还有其他证据可以证明符合计数不是电磁或地震干扰引起的。我们曾用噪声发生器测量引力辐射探测器系统的输入温度。这样可以准确说明所有显著信号源的情况，并排除输入温度的任何主要部分来源于内噪声以外的其他背景的可能性。如果符合计数是由像地震或者电磁活动这样的地球效应引起的，那么这样的信号会同时或者几乎同时到达地表或地球内部同一区域的两个实验站。然而，对于每一个同步到达两个地点的符合事件，都应该伴随有很多单个的到达，这样就会产生高于实际观测值的系统噪声水平。我们还测量了6个月内马里兰站一对引力辐射探测器的符合计数率。在实验误差范围内，同一站中两个探测器的符合计数率与另一站中两个探测器的符合计数率是完全相同的。这个结果表明：在本文涉及的灵敏度范围内，与局部环境的隔离是足够好的，并且观测到的符合计数不是由电磁和地震干扰引起的。 [英文](#)

1,000千米的距离太远，因此不太可能用宇宙线簇射来解释符合事件。尽管如此，研究宇宙线带电粒子的影响还是很重要的。桑德斯·沃尔教授、高朗·尤德教授和戴维·埃兹罗博士在马里兰站的一个引力辐射探测器上装备了切伦科夫辐射计数器，后来又装备了米方塑料闪烁体。他们在宇宙线簇射与引力辐射探测器符合计数之间没有观测到显著的关联 [7]。 [英文](#)

我们对同样位于马里兰站的一个1,661赫兹引力辐射探测器和另一个5,000赫兹模式引力辐射探测器之间的符合计数进行了研究。没有观测到超过偶然符合计数率的符合计数。接下来的研究表明：5,000赫兹模式是一个弯曲模式，而不是一个压缩模式。广义相对论预言这种弯曲模式不会和引力辐射发生相互作用。两个探测器之间缺乏符合计数的事实就成为否定1,661赫兹下符合计数来自非引力辐射源的证据。 [英文](#)

另有一些文章提出证据指出：观测到的符合计数具有各向异性，最大值出现在银河系中心方向^[8]。圆盘实验的结果与爱因斯坦纯张量理论的预言一致。局部环境的小作用会显著影响各向异性。为了适当地平均这些影响，最少需要6个月的数据。本文采用的磁带记录在时间上不连续。空白以及记录器故障使得数据不足以用来进行各向异性的研究。对计算机发现的符合事件列表进行的表观检查显示，这些数据与之前基于对笔墨记录表格进行人工观测研究而得到的各向异性实验结果一致。

英文

现有数据没有人为观测偏差。除了要求有相当平滑的前沿之外，对预期脉冲的持续时间或其形状都没有作任何别的假设。这一点的重要性在于，噪声的加入会改变接收到的脉冲的形状。我们认为已经可以毫无疑问地接受，在1,000千米基线两端的引力辐射探测器是由一个共同的源激发的。这是相互作用的结果，这个作用既不是地震或电磁，也不是来自宇宙线带电粒子。

英文

感谢戴森、特林布尔和林戈与我进行了有价值的讨论，还要感谢格雷茨和佩雷格林对引力辐射探测器的维护和操作。美国国家科学基金会和马里兰大学计算机科学中心都为这项工作提供了部分支持。

英文

（何钧 翻译；张元仲 审稿）

Image Formation by Induced Local Interactions: Examples Employing Nuclear Magnetic Resonance

P. C. Lauterbur

Physicists in the 1940s learned to exploit the response of nuclear spins to applied magnetic fields to probe the structure of solids and liquids. A magnetic field splits the energies of spin states of a nucleus, and radio-frequency radiation can induce transitions between them. Because different nuclei absorb energy at different frequencies, and because the chemical environment also influences this frequency, the technique of nuclear magnetic resonance (NMR) can be used to probe the chemical structure of a sample. Here chemist Paul Lauterbur shows how to adapt this technique to produce detailed spatial images. The technique, known now as magnetic resonance imaging (MRI), is used ubiquitously in basic and applied science, especially medicine. In 2003 Lauterbur shared a Nobel Prize with Peter Mansfield, who developed methods for analysing MRI signals. [中文](#)

AN image of an object may be defined as a graphical representation of the spatial distribution of one or more of its properties. Image formation usually requires that the object interact with a matter or

radiation field characterized by a wavelength comparable to or smaller than the smallest features to be distinguished, so that the region of interaction may be restricted and a resolved image generated. 中文

This limitation on the wavelength of the field may be removed, and a new class of image generated, by taking advantage of induced local interactions. In the presence of a second field that restricts the interaction of the object with the first field to a limited region, the resolution becomes independent of wavelength, and is instead a function of the ratio of the normal width of the interaction to the shift produced by a gradient in the second field. Because the interaction may be regarded as a coupling of the two fields by the object, I propose that image formation by this technique be known as zeugmatography, from the Greek ζευγμα, “that which is used for joining”. 中文

The nature of the technique may be clarified by describing two simple examples. Nuclear magnetic resonance (NMR) zeugmatography was performed with 60 MHz (5 m) radiation and a static magnetic field gradient corresponding, for proton resonance, to about 700 Hz cm⁻¹. The test object consisted of two 1 mm inside diameter thin-walled glass capillaries of H₂O attached to the inside wall of a 4.2 mm inside diameter glass tube of D₂O. In the first experiment, both capillaries contained pure water. The proton resonance line width, in the absence of the transverse field gradient, was about 5 Hz. Assuming uniform signal strength across the region within the transmitter-receiver coil, the signal in the presence of a field gradient represents a one-dimensional projection of the H₂O content of the object, integrated over planes perpendicular to the gradient direction, as a function of the gradient coordinate (Fig. 1). One method of constructing a two-dimensional projected image of the object, as represented by its H₂O content, is to combine several projections, obtained by rotating the

object about an axis perpendicular to the gradient direction (or, as in Fig. 1, rotating the gradient about the object), using one of the available methods for reconstruction of objects from their projections¹⁻⁵. Fig. 2 was generated by an algorithm, similar to that of Gordon and Herman⁴, applied to four projections, spaced as in Fig. 1, so as to construct a 20×20 image matrix. The representation shown was produced by shading within contours interpolated between the matrix points, and clearly reveals the locations and dimensions of the two columns of H_2O . In the second experiment, one capillary contained pure H_2O , and the other contained a 0.19 mM solution of MnSO_4 in H_2O . At low radio-frequency power (about 0.2 mGauss) the two capillaries gave nearly identical images in the zeugmatogram (Fig. 3a). At a higher power level (about 1.6 mGauss), the pure water sample gave much more saturated signals than the sample whose spin-lattice relaxation time T_1 had been shortened by the addition of the paramagnetic Mn^{2+} ions, and its zeugmatographic image vanished at the contour level used in Fig. 3b. The sample region with long T_1 may be selectively emphasized (Fig. 3c) by constructing a difference zeugmatogram from those taken at different radio-frequency powers.

中文

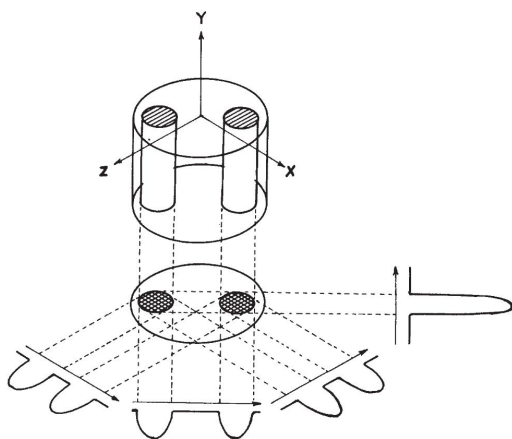


Fig. 1. Relationship between a three-dimensional object, its two-dimensional projection along the Y-axis, and four one-dimensional projections at 45° intervals in the XZ-plane. The arrows indicate the gradient directions. 中文



Fig. 2. Proton nuclear magnetic resonance zeugmatogram of the object described in the text, using four relative orientations of object and gradients as diagrammed in Fig. 1. [中文](#)

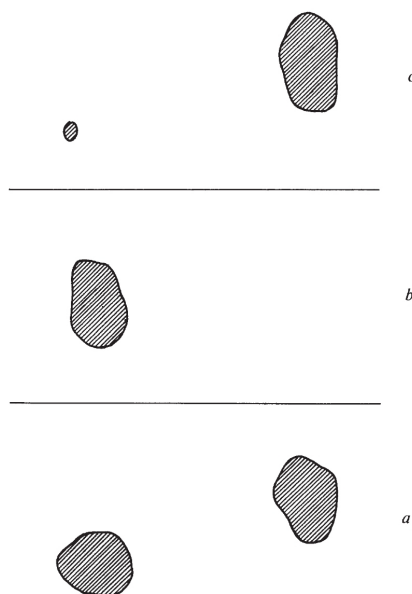


Fig. 3. Proton nuclear magnetic resonance zeugmatograms of an object containing regions with different relaxation times. *a*, Low power; *b*, high power; *c*, difference between *a* and *b*.

[中文](#)

Applications of this technique to the study of various inhomogeneous objects, not necessarily restricted in size to those commonly studied by magnetic resonance spectroscopy, may be anticipated. The experiments outlined above demonstrate the ability of the technique to generate pictures of the distributions of stable isotopes, such as H and D, within an object. In the second experiment, relative intensities in an image were made to depend upon relative nuclear relaxation

times. The variations in water contents and proton relaxation times among biological tissues should permit the generation, with field gradients large compared to internal magnetic inhomogeneities, of useful zeugmatographic images from the rather sharp water resonances of organisms, selectively picturing the various soft structures and tissues. A possible application of considerable interest at this time would be to the *in vivo* study of malignant tumours, which have been shown to give proton nuclear magnetic resonance signals with much longer water spin-lattice relaxation times than those in the corresponding normal tissues⁶. 中文

The basic zeugmatographic principle may be employed in many different ways, using a scanning technique, as described above, or transient methods. Variations on the experiment, to be described later, permit the generation of two- or three-dimensional images displaying chemical compositions, diffusion coefficients and other properties of objects measurable by spectroscopic techniques. Although applications employing nuclear magnetic resonance in liquid or liquid-like systems are simple and attractive because of the ease with which field gradients large enough to shift the narrow resonances by many line widths may be generated, NMR zeugmatography of solids, electron spin resonance zeugmatography, and analogous experiments in other regions of the spectrum should also be possible. Zeugmatographic techniques should find many useful applications in studies of the internal structures, states, and compositions of microscopic objects.

中文

(242, 190-191; 1973)

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Received October 30, 1972; revised January 8, 1973.

References:

1. Bracewell, R. N., and Riddle, A. C., *Astrophys. J.*, **150**, 427 (1967).
2. Vainshtein, B. K., *Soviet Physics-Crystallography*, **15**, 781 (1971).
3. Ramachandran, G. N., and Lakshminarayan, A. V., *Proc. US Nat. Acad. Sci.*, **68**, 2236 (1971).
4. Gordon, R., and Herman, G. T., *Comm. Assoc. Comput. Mach.*, **14**, 759 (1971).
5. Klug, A., and Crowther, R. A., *Nature*, **238**, 435 (1972).
6. Weisman, I. D., Bennett, L. H., Maxwell, Sr., L. R., Woods, M. W., and Burk, D., *Science*, **178**, 1288 (1972).

诱导局域相互作用成像：核磁共振应用实例

劳特布尔

20世纪40年代，物理学家们掌握了利用核自旋对外加磁场的响应来探索固体和液体的结构的方法。磁场使核自旋态发生能级分裂，而射频辐射可使原子核发生能级跃迁。由于不同的核吸收不同频率的能量，并且化学环境也会影响到这个频率，因此核磁共振技术就可以用来探索样品的化学结构。本文中，化学家保罗·劳特布尔展示了如何利用这一技术获得清晰的空间影像。这一技术——现在被称为磁共振成像，已在基础和应用科学，尤其是在医学中都得到了广泛应用。2003年，劳特布尔和彼得·曼斯菲尔德（后者发展了磁共振成像信号分析方法）共同获得了诺贝尔奖。

[英文](#)

一个物体的像可以定义为它的一个或多个特征量的空间分布的图像化表示。成像通常需要该物体与某种物质或辐射场相互作用，且与之作用的物质或辐射场的波长应与期望分辨的物体特征量的最小尺寸相当或更小，从而可能限定相互作用的区域，并产生足够分辨率的图像。

[英文](#)

利用诱导局域相互作用可以克服上述波长对成像分辨率的限制，并由此可发展出一类新成像方法：通过施加一个额外场可以将物体与辐射场的相互作用限制在一个有限区域。由此而获得的像的分辨率只是相互作用的标准宽度与由额外场梯度产生的变化量的比值相关的函数，而与波长无关，因为这个相互作用可以看作是两个场借助物体而产生耦合，故建议将基于此技术的成像命名为“zeugmatography”（常被翻译为“共轭成像法”，“结合成像法”或“组合层析成像法”），其来源于希腊语“ζευγμα”，是“结合”的意思。

[英文](#)

下面举两个简单的例子来说明该技术的本质。核磁共振共轭成像（现在一般称为“核磁共振成像”或“磁共振成像”）实验采用60 MHz（波长为5 m）的射频场和一个带梯度的静磁场，对质子共振而言，该静磁场的梯度场强为700 Hz·cm⁻¹。实验样品是两根装有水（H₂O）的内径为1 mm的薄壁玻璃毛细管，它们被置于一根装有重水（D₂O）的内径为4.2 mm的玻璃管中。在第一个实验中，两根毛细管中均装的是纯水，在未施加横向梯度场时，质子共振线宽约为5 Hz。假定发射—接收线圈区域内的信号强度均匀，在施加梯度场后获得的信号代表了实验样品中水含量分布沿梯度垂直方向的一维投影，它是与梯度坐标相关的函数（如图1所示）。绕垂直于梯度场方向的轴转动实验样品（或如图1所示，以样品为轴转动梯度场），获得实验样品的一系列一维投影。以此为基础，采用投影重建的方法^[1-5]可构建出表示实验样品水含量分布的二维投影像。利用如图1所示的四个不同方向的一维投影并采用类似于戈登和赫尔曼的投影重建算法^[4]，可以构建出如图2所示的20×20的图像矩阵，此图像是由矩阵点间轮廓线插值的描影法来显示，它清楚地表征了这两组圆柱体水的位置和大小。在第二个实验中，一根毛细管内装的是纯水，另一根毛细管中装的是0.19 mM浓度的MnSO₄水溶液。在低射频功率（功率约为0.2 mGs）下，这两组毛细管水呈现出几乎相同的核磁共振像（如图3a所示）。但在高功率射频场（功率约为1.6 mGs）作用下，纯水样品的信号被饱和，导致其在同标准等高线图显示的核磁共振像消失；而对于加入顺磁性Mn²⁺离子的水溶液样品，由于其自旋—晶格弛豫时间T₁变短，故信号不容易饱和，其核磁共振像仍然出现，如图3b所示。比较不同射频功率作用下生成的核磁共振像的差分像，即可发现样品中T₁时间长的区域得到选择性的突出显示（如图3c所示）。 英文

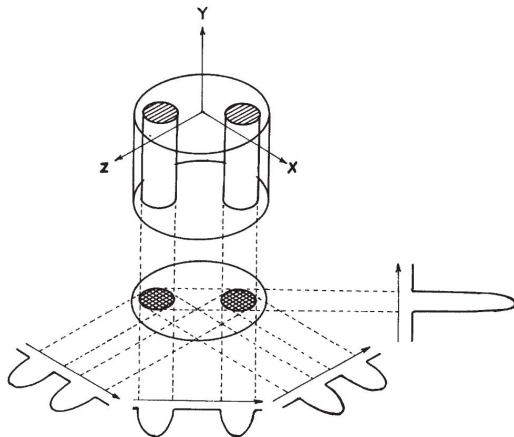


图1．核磁共振成像实验的三维示意图：其二维投影方向沿着Y轴，四个45°间隔的一维投影位于XZ平面内，箭头所示方向为梯度场方向。 英文



图2．样品的质子核磁共振像：利用如图1所示的四个不同方向的一维投影按文中所述的投影重建方法构建而成 英文

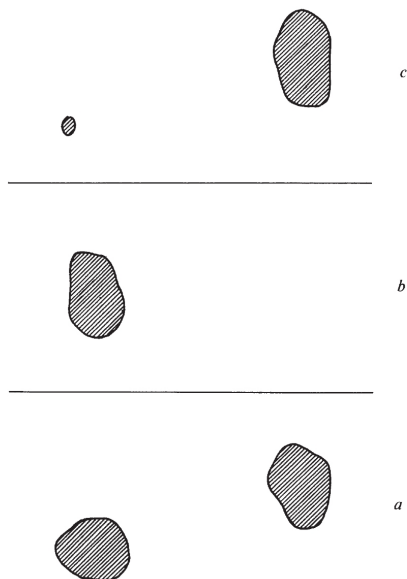


图3．样品中弛豫时间不同的区域的质子核磁共振像：a，低强度射频；b，高强度射频；c，图a和图b的差分像 [英文](#)

核磁共振成像是不同于那些传统的核磁共振谱技术，不太受样品大小（以及均匀性）的限制，可以预期，此技术将会被应用于诸多非均匀样品的研究。上述实验证明，这项技术能够用于获得样品中稳定同位素（如H和D）含量的分布图像。在第二个实验中，图像的相对强度取决于对应核的弛豫时间的长短。根据生物组织中水的含量和质子弛豫时间的不同，当外加的梯度场远大于生物组织的内部梯度场时，可以利用有机体中相对窄的水共振信号获得有用的核磁共振像，实现各种生物体软组织的选择性成像。当前，一个非常诱人的可能应用是恶性肿瘤的活体研究。因为恶性肿瘤组织中水的质子自旋-晶格弛豫时间比相应正常组织中的要长得多^[6]。 [英文](#)

基于上文提到的扫描技术或瞬态方法的共轭成像的基本原理有着诸多不同的潜在应用。将上述实验进行拓展延伸，能够产生显示样品的化学成分、扩散系数以及依靠谱学技术测量的其他特征量的二维或三维图像，这些在以后描述。核磁共振成像技术在液体和液体状的体系中的应用简单且引人注目，这是因为此时梯度场足够大且足以移动较窄的共振信号使其空间位置得以区分。而类似的固体核磁共振共轭成像、电子自旋共振共轭成像以及其他频谱学的共轭成像同样有实现的可能。可以预

见，共轭成像技术未来将在微观物质的内部结构、状态和构成的研究中也
也会被广泛应用。 [英文](#)

（王耀杨 翻译；刘朝阳 陈方 审稿）

Experiments on Polishing of Diamond

J. Wilks

The interest of this contribution from John Wilks at Oxford is not so much in the specific findings—that polished diamond is microscopically rough—but in the way it touches on several themes in materials science that have become increasingly relevant in recent decades: the microscopic mechanisms of lubrication and friction, the microtopography of surfaces, and the quest for superhard materials. Wilks highlights the fact that polishing a solid surface is usually different to abrading it, involving local melting because of intense frictional heating. But as only diamond powder itself can polish diamond, abrasion must here be the mechanism: the powder chips the surface and leaves it rough in a way that depends on the orientation of the crystal planes. 中

文

Polished diamond surfaces have unusual properties because polishing of the brittle material generally proceeds by mechanical chipping. 中文

DIAMONDS are shaped and polished to produce gem stones by methods which have remained essentially unchanged for several hundred years. Yet it is only recently that the physical basis of these

operations has been studied, and their unusual features fully appreciated. This article outlines the principal features of the polishing process and describes some recent experiments which illustrate the very characteristic nature both of the process itself and the polished surfaces produced. We shall show that these perhaps unique properties result from the very hard and brittle nature of the diamond. [中文](#)

The usual method of polishing a diamond is to hold it either against the face of a rotating cast-iron wheel (or scaife) charged with a suspension of fine diamond powder in a light oil, or against the face of a wheel in which diamond powder is bonded into a metal matrix. One of the most striking features of this method is that if a cube face is prepared on the diamond, it turns out that the rate of removal of material during polishing with a bonded wheel in a direction parallel to a cube axis is about 100 times greater than if the same face is polished in a direction at 45° to a cube axis. Similar effects are observed on other faces, and even greater differences are evident when polishing on a cast-iron scaife, as the more resistant directions of the diamond tend to knock the powder out of the scaife. [中文](#)

In preparing a gem stone from a rough diamond it is necessary to remove a certain amount of material to position the facets before polishing them. Another unusual feature is that this removal of material is effected in almost the same way as polishing, except that larger sized diamond powder is used to remove material quickly. For most materials, polishing and the removal of material by abrasion are quite different processes. Removal of material is generally achieved by the use of an abrasive powder in what is essentially a cutting process; the powder is harder than the specimen, and it either gouges out material, or sets up stresses which lead to cracking after it has moved on. By contrast, polishing is generally a smearing process, brought about by rubbing with a second material to produce high

temperatures in the small regions of true contact between the asperities on the two surfaces; the high temperatures result in local melting of the asperities, which are then smoothed out. It follows that to polish a specimen, we must use polishing material with a higher melting point, so that on rubbing, the specimen melts and flows first. For further details of the general features of abrasion and polishing, see for example, Bowden and Tabor¹ and Cottrell². [中文](#)

In view of all this, one would expect to encounter difficulties both in removing material from diamonds and in polishing them. As far as the removal of material is concerned, there is no harder substance than diamond which can be used to produce abrasive cutting. In rubbing operations, the high thermal conductivity of diamond will tend to reduce the temperature of the hot spots at the areas of local contact, whereas high temperatures are required to effect even the conversion of diamond to graphite. Thus, conditions seem unfavorable for both abrasion and polishing, but in fact the traditional methods used by the diamond industry abrade and polish diamond quite successfully. The rate of abrasion is relatively low, but a high polish can readily be obtained, and a diamond surface may be worked to the standard of a good optical flat³. [中文](#)

The first scientific experiments on the polishing process were made more than 50 years ago by Tolkowsky⁴, who proposed that both abrasion and polishing proceed by mechanical chipping on a microscopic scale. This chipping will be controlled by the lie of the cleavage planes relative to the direction of abrasion, and will therefore occur more readily in some directions than others, thus giving rise to very considerable differences in rates of abrasion. To indicate the geometrical arrangement of the cleavage planes, Tolkowsky made use of a model of diamond built up from small identical octahedral and tetrahedral shaped blocks, and thus explained the variations of the hardness on both the cube and the dodecahedron planes^{4,5}. [中文](#)

Tolkowsky was principally interested in practical applications and his conclusions about how to polish and abrade diamonds soon found their way into the diamond trade, as did his other research on the best way to lay out the facets of a diamond so as to produce the well known brilliant cut. On the other hand, his account of the underlying mechanism was not widely published, and attracted little attention. His treatment was criticized on the grounds that diamond is certainly not built up of equally sized elementary blocks as in his model, but the essential function of the model is to indicate the positions of the cleavage planes—and this it does correctly. It now turns out, as the result of various experiments on diamond over the past 15 years, together with increasing knowledge of the nature of brittle materials, that Tolkowsky's views are essentially correct. [中文](#)

One of the crucial features of the above experiment observed but not stressed by Tolkowsky⁴, is that the rate of removal of material is proportional to the total number of revolutions of the polishing scaife but does not depend on its speed. This result, confirmed by Wilks and Wilks^{5,6}, shows that thermally activated processes play no significant part in the removal of material. The rubbing together of two materials produces heating at the areas of true local contact, and this excess temperature increases rapidly with the speed of rubbing¹. The fact that the abrasion per revolution does not increase with rising speed of rubbing clearly demonstrates that local hot spots play no significant part in the wear process. In particular, it rules out the possibility that the diamond is worn away by either burning or conversion to graphite, as suggested by Seal⁷. On the other hand, one would expect the same amount of material to be removed by each revolution of the wheel if the abrasion proceeds by a mechanical chipping or cleavage process. [中文](#)

The conditions necessary for materials to fail by chipping or brittle fracture have been discussed by several authors, for example Kelly⁸.

Kelly, Tyson and Cottrell⁹ have considered whether an ideal crystal free of imperfections will fail plastically by shear or by brittle fracture under tension. They show that for face centred metals such as copper, gold and silver, the stress required to produce fracture is about 30 times greater than that to produce shear, and that failure always occurs by plastic deformation rather than cleavage. On the other hand, the calculations show that, of the substances considered, sodium chloride and diamond are most likely to fail by brittle fracture. The critical stresses for shear and cleavage in sodium chloride and diamond are approximately equal, but the calculations are not sufficiently refined to indicate which process is preferred. These calculations are, however, for ideal crystals and the essential question for real materials is whether the presence and motion of dislocations will permit plastic flow before fracture. [中文](#)

Dislocations in diamond have been observed by Evans¹⁰ who prepared specimens of diamond by etching, and viewed the dislocations directly in the transmission electron microscope. They are also clearly delineated by the X-ray topograph techniques of Frank and Lang¹¹. Calculations mentioned by Evans¹² suggest that the movement of the dislocations will be inhibited by the necessity of breaking carbon-carbon bonds. Their motion has been studied experimentally by Evans and Wild^{12,13} who took specimens of diamond in the form of thin slabs, loaded them in the middle, and observed whether they failed by fracture or plastic deformation. They found that at low temperatures the beam always failed by fracture, but that an increasing amount of plastic flow was observed as the temperature exceeded 1,500 °C. Hence dislocations in diamond may be quite mobile, but at room temperature are held back by obstacles which can only be overcome by considerable thermal activation. As the rates of abrasion and polish in the experiments referred to above were independent of the temperature of local hot spots, one concludes that the abrasion was not accompanied by any thermally activated motion of dislocations.

It is sometimes suggested that plastic flow in diamond may be produced by conditions of intense local pressure. The effect of pressure on brittle materials is sometimes surprising, for example it is possible to compress a slab of brittle material, such as rock salt, to half its initial thickness without producing cracking¹⁴, and Howes and Tolansky¹⁵ have argued that the ring cracks produced by indenting diamond with steel spheres show evidence of plastic flow. Later studies by Lawn and Komatsu¹⁶ of the region round such a crack, using X-ray topography, show no sign of plastic deformation, and Frank and Lawn¹⁷ have since shown that the cracks may be described in terms of fracture processes. 中文

We conclude that the mechanism of abrasion is one of mechanical chipping. This conclusion is supported by a study of the area around an abrasion mark, by Frank, Lawn, Lang and Wilks¹⁸ using X-ray topography, which shows that the state of strain in the surface is consistent with stresses set up by fracture processes and not by plastic flow. We believe that there is no convincing evidence for the motion of dislocations in any of the relevant abrasion and polishing experiments, although claims to have observed plastic flow in diamond at room temperature have been made by Brookes¹⁹ and by Gane and Cox²⁰. Brooks indented a diamond surface with a Knoop indenter made of diamond and claimed that the form of the indentation indicated that plastic flow had occurred. A careful study of Brookes's indentations, however, show clear indications of brittle fracture (Fig. 1), which appear to have been obscured in the earlier micrographs. The observations of Gane and Cox were based on the study of thin diamond wedges pressed against each other, but their evidence is at best inconclusive. Even under these rather specialized conditions, there is no clear evidence that plastic flow and motion of dislocations took place. 中文

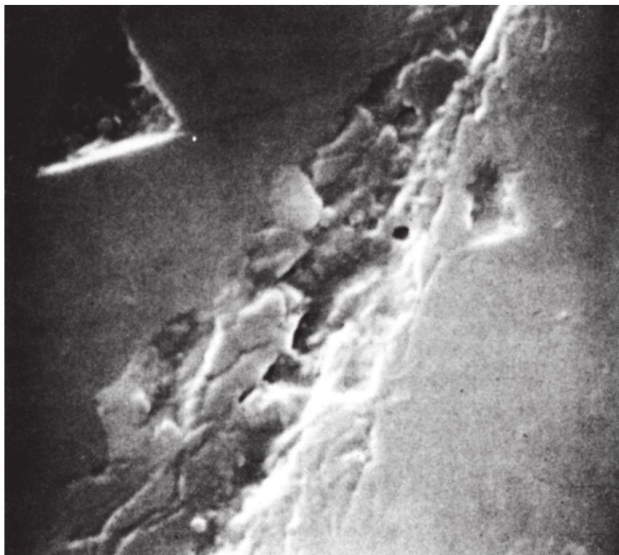


Fig. 1. Scanning electron microscope micrograph of a diamond surface indented with a Knoop indenter ($\times 8,400$). [中文](#)

We shall now describe three sets of experiments which confirm the fracture process and illustrates the unusual properties of polished diamond surfaces. In the first set a simple micro-abrasion tester²¹ was used to study the variation of the rate of removal of material—in short the hardness of the diamond—with the orientation of the surface and the direction of polish. The hardness is often extremely sensitive to any change in the orientation of the facet being abraded. For example, Fig. 2 shows the relative rates of removal of material on surfaces obtained by tilting an octahedron plane about the (011) axis indicated in the sketch plan. The crosses show the rate of removal of material for abrasion in the direction A_x , and the circles the rate in the direction A_0 . We see that on a true octahedron plane the rate of removal in the direction A_0 is more than twice that in the direction A_x , but that a tilt of only about 1° is sufficient to reverse the relative hardness. [中文](#)

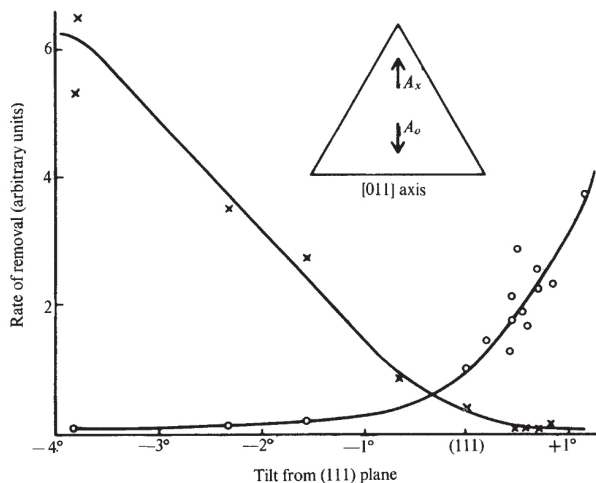


Fig. 2. The relative rates of removal of material by grinding on surfaces near to an octahedron plane. The symbols $\circ$ and $\times$ correspond to the directions shown in the inset. 中文

These orientation effects are not explained by Tolkowsky's treatment, which also has difficulty in discussing the octahedron face. The variation in rates of abrasion on cube and dodecahedron faces is explained by the lie of the cleavage planes which results in the production of a different structure by abrasion in different directions. As the cleavage planes run parallel to an octahedron face, the treatment seems to predict a uniform surface with no easy and hard directions of abrasion, in contrast with the measurements. To explain this point, we must consider the behavior of tilted octahedron facets.

中文

A diamond surface which has been polished by a process of mechanical chipping will not be atomically flat but must consist of hills and valleys bounded by an irregular arrangement of cleavage planes as shown very schematically in Fig. 3A. It follows that abrasion proceeds by the removal of material from the tops or sides of the microhills. If Fig. 3A represents a section through an octahedron face, parallel to the directions A_x and A_o , the lie of the cleavage planes is such that the most likely sites for the removal of material are the edges a and b (ref. 5). It also follows that the easiest direction of abrasion is A_o , and that most of the material is then removed from the

edges b . If, on the other hand, a face is prepared inclined to the octahedron face by a small angle, the lie of the cleavage planes remains the same, so the structure of the microhills is as shown schematically in Fig. 3B. Topographically, the abrading wheel must be presented with an increased number of b type edges, and the hardness correspondingly reduced. Similarly a tilt in the opposite direction increases the hardness. 中文

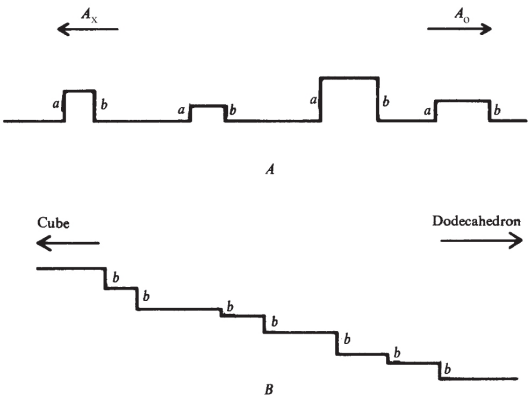


Fig. 3. Schematic diagrams of polished diamond surfaces (see text). 中文

One also expects that the change in hardness with tilt may be very rapid. If the linear dimensions of the microhills are all of the same order of magnitude h , the average distance between hills in contact with the abrading wheel will be much larger because the areas of real contact are less than the nominal areas by factors of order 10^4 . Thus the distance between the hills may be of the order of $100h$, so that a tilt of 1° would be sufficient to change the topography of Fig. 3A to that of Fig. 3B, and thus approximately double the number of sites of easy abrasion. Similar arguments may be applied to account for the hardness of both true and tilted cube and dodecahedron faces. All the predictions that can be made from the model are in accord with experiment⁵. 中文

We have also made studies of the jagged nature of polished diamond surfaces, implied by our abrasion experiments, by observing the friction of diamond sliding on diamond in air. Some time ago Seal⁷

showed that the friction of a polished cube surface varies with the azimuthal angle of sliding, with a four-fold symmetry. This result is at first surprising, as Bowden and Hanwell²² have shown that diamond surfaces in air are covered by a strongly adsorbed film which reduces the friction by an order of magnitude below its value for clean surfaces in high vacuum. Thus even though the diamond surface is covered by a tenacious film of adsorbed gases, the symmetry of the diamond is projected through the film. [中文](#)

The friction between diamonds in air was first measured by Bowden and Young²³, and Bowden and Tabor²⁴ later pointed out that their results showed an approximate relation between the friction μ and the load W of the form $\mu \propto W^{-1/3}$. They then suggested that this relation arose because of adhesion processes between the actual areas of true contact, and that this adhesion was responsible for the friction. Recent measurements by Casey and Wilks²⁵ show, however, that the friction is independent of the load over a wide range of loads, including the range of the earlier experiments. It therefore seems that the mechanism responsible for friction is not one of adhesion, a result which is confirmed by the fact that the friction remains unchanged when the diamond surface is lubricated with light oil. [中文](#)

The observed behavior of the friction is readily explained by a roughness (or ratchet) type mechanism associated with the jagged nature of a polished diamond surface. That is, the friction force arises from the work required to move the two diamond surfaces against the normal load as they are forced apart when asperities ride over each other. Some of this work will degenerate into heat when the jagged and irregular surfaces come together again, because the return motion will tend to be abrupt and irreversible. The work of separation is proportional to the load, so this type of mechanism leads to a value of the friction which is independent of the load. We believe that this mechanism accounts quite generally for the friction of diamond on

diamond in air as discussed in more detail by Casey and Wilks²⁵. The adsorbed film acts as a lubricant, which reduces adhesion and the high friction observed in a vacuum, but does not obscure the structure of the surface. 中文

Fig. 4a shows the results of recent measurements on the friction of a diamond sliding over a polished cube surface which are similar to those of Seal⁷. The diamond surface had been polished in the usual way and was therefore covered by an array of fine polishing lines or grooves running parallel to a cube axis. Nevertheless, the friction shows a full four-fold symmetry, having the same value in directions parallel and perpendicular to the grooves. We then repolished a surface by abrasion in a hard direction at 45° to a cube axis, until the original polishing lines were replaced by a new set at 45° to the original direction. The friction on this new surface is shown in curve *b*; the friction has quite different values and exhibits only a two-fold symmetry, the lowest values being for directions parallel to the direction of polish. 中文

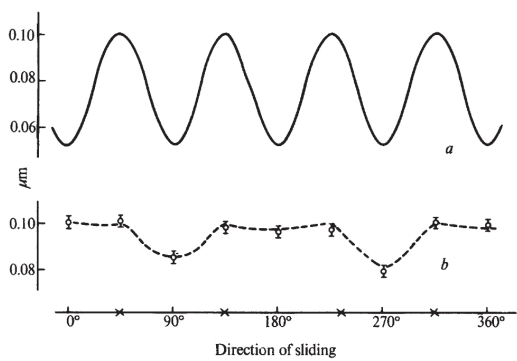


Fig. 4. The friction of a diamond sliding over a polished cube surface as a function of azimuthal angle. *a*, After polishing in the normal soft direction; *b*, after polishing in a hard direction.

The symbols × indicate the positions of the cube axes. 中文

These results confirm that the topography of a polished surface is determined by mechanical chipping. Just as abrasion proceeds at different rates in different directions, because of the orientation of the

cleavage planes, so surfaces prepared by polishing in different directions will have different structures. As discussed by Tolkowsky, a surface polished in the usual direction parallel to a cube axis will present a jagged surface with a four-fold symmetry. If, however, the diamond is polished in one of the hard directions, the surface structure will tend to take the form of grooving parallel to the direction of polish, with the two-fold symmetry shown in the friction measurements. We are at present extending our studies to observe the wear effects associated with repeated passes of the stylus over the same area of surface. [中文](#)

The third set of experiments are concerned with observing the surface structure of polished diamonds by using high resolution electron microscopy and carbon replica techniques. The structure turns out to be irregular and on a very small scale; therefore, particular care must be taken to ensure that the micrograph is in focus and free of astigmatism. Fig. 5 shows micrographs prepared under carefully controlled and similar conditions, except that the replica of Fig. 5a was taken from a freshly cleaved surface of mica, and those of Fig. 5b and c from polished surfaces of diamond. The greater contrast in the diamond micrographs indicates that the surface is much rougher than the mica and that the scale of the irregularities is of the order of 50 Å.

[中文](#)

The micrographs in Fig. 5b and c were prepared from the same stone, using the same technique, but Fig. 5b was taken from a cube surface polished in the usual way, and Fig. 5c from a polished octahedron face. We have also observed similar structures on the cube and octahedron faces of a second diamond, and also a different characteristic structure on the dodecahedron faces. These results confirm the fact, well known to diamond polishers, that the quality of polish depends on the particular face being polished, as follows from the mechanical nature of the polishing process. One expects the

surface structure to be delineated, at least to some extent, by cleavage planes. On a cube surface, the traces of these cleavage planes will lie at 45° to the direction of polish, and it is interesting to note that there are features lying in these directions. Further details of our results, together with details of the replication technique, will be published elsewhere. [中文](#)

Diamond is perhaps unique in that an apparently highly polished surface may in fact be mechanically rough on a microscopic scale, a result which is the consequence of its brittleness. We are at present applying these results to the use of diamond as cutting tools for machining metals, as both the rate of wear of the diamond, and the finish produced on the metal, depend sensitively on the surface structure of the tool. For example, the rate of wear of two single-diamond turning tools with identical external geometry, but fabricated so that the diamonds have different crystallographic orientations, show wear rates which are reproducible, and differ by a factor of 7 (ref. 26). The wear in this particular experiment, in which the diamonds turned an aluminum-silicon alloy of the type used to manufacture motor car pistons, was almost certainly controlled by the lie of the fracture planes as discussed above, and these are quite different in the two crystallographic orientations. Further experiments are being continued on both the wear of diamonds and the finish they produce. [中文](#)

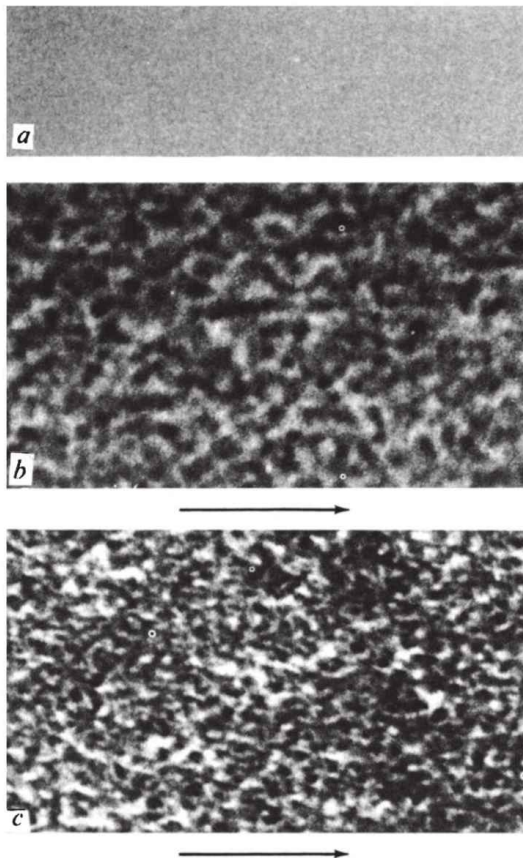


Fig. 5. Micrographs of replicas taken from *a*, cleaved mica; *b*, a polished cube face of diamond; *c*, a polished octahedron face of diamond. The arrows indicate the directions of polish. ($\times 1,000,000$). [中文](#)

I thank Mr M. Casey for Figs. 1 and 4, Dr E. M. Wilks for Fig. 2, Dr D. Driver and Mr A. G. Thornton for the micrographs in Fig. 5, and the Science Research Council and De Beers Industrial Diamond Division for their support of this work. [中文](#)

(243, 15-18; 1973)

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References:

1. Bowden, F. P., and Tabor, D., *The Friction and Lubrication of Solids*, **1** (Clarendon, 1950); **2** (Clarendon, 1964).

2. Cottrell, A. H., *The Mechanical Properties of Matter* (Wiley, 1964).
3. Wilks, E. M., *J. Opt. Soc. Amer.*, **2**, 84 (1953).
4. Tolkowsky, M., thesis, Univ. London (1920).
5. Wilks, E. M., and Wilks, J., *J. Phys. D.*, **5**, 1902 (1972).
6. Wilks, E. M., and Wilks, J., *Phil. Mag.*, **38**, 158 (1959).
7. Seal, M., *Proc. Roy. Soc.*, **A248**, 379 (1958).
8. Kelly, A., *Strong Solids* (Clarendon, 1966).
9. Kelly, A., Tyson, W. R., and Cottrell, A. H., *Phil. Mag.*, **15**, 567 (1967).
10. Evans, T., *Physical Properties of Diamond* (edit. by Berman, R.), 116 (Clarendon, 1965).
11. Frank, F. C., and Lang, A. R., *Physical Properties of Diamond* (edit. by Berman, R.), 69 (Clarendon, 1965).
12. Evans, T., *Science and Technology of Industrial Diamonds*, **1** (edit. by Burls, J.), 105 (Industrial Diamond Information Bureau, London, 1966).
13. Evans, T., and Wild, R. K., *Phil. Mag.*, **12**, 479 (1965).
14. Bowden, F. P., and Tabor, D., *The Friction and Lubrication of Solids*, **2**, 118 (Clarendon, 1964).
15. Howes, V. R., and Tolansky, S., *Proc. Roy. Soc.*, **A230**, 287, 294 (1955).
16. Lawn, B. R., and Komatsu, H., *Phil. Mag.*, **14**, 689 (1966).
17. Frank, F. C., and Lawn, B. R., *Proc. Roy. Soc.* **A299**, 291 (1967).
18. Frank, F. C., Lawn, B. R., Lang, A. R., and Wilks, E. M., *Proc. Roy. Soc.*, **A301**, 239 (1967).
19. Brookes, C. A., *Nature*, **228**, 660 (1970).
20. Gane, N., and Cox, J. M., *J. Phys. D.*, **3**, 121 (1970).
21. Wilks, E. M., and Wilks, J., *The Physical Properties of Diamond* (edit. by Berman, R.), 221 (Clarendon, 1965).
22. Bowden, F. P., and Hanwell, A. E., *Proc. Roy. Soc.* **A295**, 233 (1966).
23. Bowden, F. P., and Young, J. E., *Proc. Roy. Soc.* **A208**, 444 (1951).
24. Bowden, F. P., and Tabor, D., *The Friction and Lubrication of Solids*, **2**, 169 (Clarendon, 1964).
25. Casey, M., and Wilks, J., *Diamond Research 1972* (Suppl. to *Ind. Diam. Rev.*), 6 (1972).
26. Casey, M., and Wilks, J., *Diamond Research 1972* (Suppl. to *Ind. Diam. Rev.*), **11** (1972).

金刚石抛光实验

威尔克斯

来自牛津的约翰·威尔克斯所做的贡献中令人感兴趣的不仅仅在于抛光的金刚石在显微镜下是粗糙的这一特定研究结果，还在于近几十年来它越来越多地涉及材料科学的若干主题：润滑和摩擦的微观机制、表面的微观形貌和对超硬物质的探求。威尔克斯强调固体表面的抛光与磨削是有区别的，抛光包括由强烈的摩擦热产生的局部熔化。但是只有金刚石粉本身能抛光金刚石，磨削一定是这种机制：粉末切削表面后，表面的粗糙情况在某种程度上取决于晶面的取向。 [英文](#)

抛光的金刚石表面具有不同寻常的性质，因为这种脆性物质的抛光通常是通过机械切削来进行的。 [英文](#)

在过去的几百年中，将金刚石加工成形和抛光以生产宝石所用的方法在本质上保持不变。一直到最近，这些操作的物理学基础才得到了研究，它们那不同寻常的特征也得到了充分的理解。本文概述了抛光过程的主要特征，并且描述了一些最近的实验，它们阐明了对于抛光过程本身和所产生的抛光表面都极有特征性的本性。我们将要说明，这些独特性质可能是由金刚石极硬且脆的本性所导致的。 [英文](#)

抛光金刚石的常规方法是將金刚石抵在覆盖着细小金刚石粉末的轻油悬浊液的旋转铸铁轮（或磨光盘）表面上，或者是抵在表面嵌入金刚石粉末的金属基体的轮表面上。这种方法一个最令人吃惊的特征是，如果要在金刚石上磨制一个立方体表面，就会发现在用黏合了粉末的轮子进行的抛光过程中，平行于立方轴方向上的磨除速率约是同一表面在与

立方轴呈 45° 角方向上的速率的100倍。在其他面上也观测到了类似的效应，在用铸铁磨光盘进行抛光时甚至发现了更为显著的速率差异，因为在金刚石更具刚性的方向上更容易磨掉磨光盘上的粉末。 [英文](#)

在把金刚石原料加工成宝石时，必须要在抛光定位刻面前切除一定量的余料。另一个不同寻常的特征就是这种材料的切除会产生与抛光几乎一样的效应，只不过为了快速切除会使用较大尺寸的金刚石粉末。对于大多数材料来说，抛光和通过磨削来切除材料是相当不同的过程。原料的切除一般是通过使用磨料粉末以本质上是切削的过程来实现的；粉末比样品更坚硬，它们在移动中或者挖去原料，或者施加应力而使样品产生破裂。与此相反，抛光一般是一个涂抹的过程，通过用另一种材料进行摩擦，在两个表面的粗糙部位之间真正接触的小区域中产生高温，高温引起粗糙部位的局部熔融，继而使其变平滑。由此可知，为了将样品抛光，我们必须使用具有较高熔点的抛光材料，以便使样品在摩擦时首先熔融和流动。关于磨削与抛光过程一般特征的更详细资料可参见鲍登和泰伯^[1]与科特雷尔^[2]的文章。 [英文](#)

考虑到上述这一切，可以预料人们在从金刚石上切除余料以及对其进行抛光时都会遇到困难。就原料的切除而言，不存在比金刚石更硬的物质可以用来进行磨削切削。在摩擦操作中，金刚石的热传导性高，将会倾向于降低局部接触区域中热位点的温度，而高温甚至是从金刚石到石墨的转化过程所必需的。因此，情况对于磨削和抛光似乎都是不利的，但事实上，金刚石工业所用的磨削和抛光金刚石的传统方法却是相当成功的。磨削速率相对来说较低，但是很容易获得高度抛光，而且金刚石表面可以作为一个良好的光学标准平面^[3]。 [英文](#)

关于抛光过程的第一个科学实验是在50多年前由托尔考斯基^[4]进行的，他提出，磨削和抛光过程都是通过微观尺度上的机械切削实现的。这一切削过程将会受到解理面的形貌相对于磨削方向的位置的控制，并且会因此在某些方向上比在另一些方向上更容易发生切削过程，从而导致颇为可观的磨削速率差异。为了说明解理面的几何排列方式，托尔考斯基使用了以同样的八面体和四面体形小块搭建的金刚石模型，并由此解释了立方体和十二面体平面上的硬度变化^[4,5]。 [英文](#)

托尔考斯基主要关心实践应用，因而他关于如何抛光和磨削金刚石的结论很快就在金刚石行业得到应用，就像他另一个关于展示金刚石刻面的最佳方式的研究导致了广为人知的明亮琢型的产生一样。另一方面，他关于潜在机制的说明却没有得到广泛发表，因此没有引起多少注意。他的处理方法遭到了批评，根据是金刚石肯定不是像他的模型中那样由同样大小的基本模块搭建而成的，但是该模型的实质功能在于说明解理面的位置——而它正确地做到了。过去15年来关于金刚石的若干实验的结果，再加上对于脆性材料本性越来越多的了解，可以证实托尔考斯基的观点实质上是正确的。 英文

上述实验中托尔考斯基观察到了但并未强调的一个关键特征^[4]，就是切除材料的速率与抛光磨盘总转数成比例，而与其速率无关。这个结果得到了威尔克斯和威尔克斯^[5,6]的确认，它表明热激发过程在材料切除中的作用并不重要。两种材料的相互摩擦使真正接触的局部区域产生了热，而且过剩温度随着摩擦速率的上升而快速增加^[1]。每转的磨削不随摩擦速率提高而增加这一事实清晰地证明局部热位点在磨削过程中不起重要作用。尤其是，它排除了西尔^[7]的观点，即金刚石通过燃烧或转化为石墨而磨削的可能性。另一方面，人们可以预想，如果磨削是通过机械切削或解理过程而进行的，那么轮的每一转会切除相同量的材料。

英文

若干位作者，比如凯利^[8]，已经讨论了关于材料通过切削或脆性断裂而破坏的必需条件。凯利、泰森和科特雷尔^[9]曾考虑，毫无缺陷的理想晶体是否会通过切变或在张力下脆性断裂发生塑性破坏。他们指出，对于诸如铜、金和银等面心金属来说，产生断裂所需的应力是产生切变所需应力的约30倍，而且破坏的产生经常是由于塑性形变而不是解理。另一方面，计算表明，在所考虑的各种物质中，氯化钠和金刚石是最容易由于脆性断裂而破坏的。氯化钠与金刚石中切变和解理的临界应力是近似相等的，但是计算还没有精细到足以指出哪一过程是更为有利的。不过，这些计算都是针对理想晶体的，而对于真实材料的实质问题是，位错的存在和运动是否会允许先塑性流动后再断裂。 英文

金刚石中的位错已被埃文斯^[10]所观测到，他用蚀刻法制备金刚石样品，然后在透射电子显微镜下直接观察到了位错。弗兰克和兰^[11]也

用X射线照相技术对其进行了清晰的描述。埃文斯^[12]所提到的计算指出位错的运动会因为必须要打破碳—碳键而被抑制。位错的运动已由埃文斯和维尔德^[12,13]进行了实验研究，他们使用具有薄板形式的金刚石样品，在其中部加置负荷，然后观察它们是因断裂还是塑性形变而破坏。他们发现，低温时样品板总是会因断裂而破坏，但是当温度超过1,500℃时，可以观测到塑性流动量的增加。因此金刚石中的位错可能具有相当的流动性，不过在室温时被某种阻碍所抑制，只有通过相当大的热激发才能克服这种阻碍。由于上面所提到的实验中的磨削和抛光速率与局部热位点的温度无关，有人断言，磨削并不伴随着任何位错的热激发运动。

[英文](#)

不时有人提出，金刚石中的塑性流动可能是由强烈的局部压力而产生的。压力对于脆性材料的影响有时会是令人惊讶的，例如，将诸如岩盐等脆性材料的平板压缩到其初始厚度的一半而不产生裂痕^[14]是有可能的，而且豪斯和托兰斯基^[15]认为，通过用钢球挤压金刚石而产生的环形裂纹可以作为塑性流动的证据。后来朗和小松^[16]利用X射线照相法对这类裂纹周围的区域的研究指出没有这种塑性形变的迹象，弗兰克和朗^[17]由此指出，可以按照断裂过程对裂纹加以描述。

[英文](#)

我们断言磨削的机制是一种机械切削。这一结论为弗兰克、朗、兰和威尔克斯^[18]用X射线照相法对磨削痕迹周围区域的研究所证实，该研究表明，表面的应变状态与断裂过程而非塑性流动所导致的应力相一致。我们相信，在任何有关磨削和抛光的实验中都不存在位错运动的可靠证据，尽管布鲁克斯^[19]以及甘恩和考克斯^[20]曾宣称在室温下观测到金刚石中的塑性流动。布鲁克斯用金刚石制成的努普压头挤压金刚石表面，并且宣称凹痕的形态表明曾发生过塑性流动。但是，对布鲁克斯凹痕的仔细研究可以看出清晰的脆性断裂迹象（图1），它在以前的显微图像中可能一直都是模糊的。甘恩和考克斯的观测是基于对彼此挤压的小块楔形金刚石的研究，但是他们的证据充其量是不确定的。即便是在这些相当特殊的条件下，也不存在发生塑性流动和位错运动的明确证据。

[英文](#)

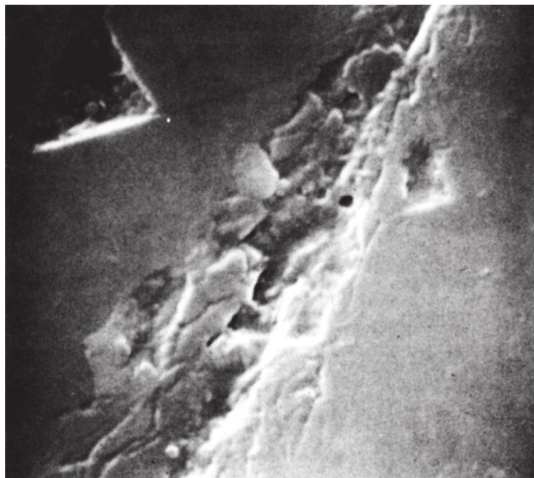


图1．用努普压头挤压金刚石表面得到的扫描电子显微图像（ $\times 8,400$ ） 英文

现在我们要介绍三组实验，它们确证了断裂过程并且描绘出抛光后金刚石表面不同寻常的性质。第一组实验是用一个简单的微型磨削检测器来研究材料切除速率^[21]——简而言之就是金刚石的硬度——随表面指向和抛光方向的变化。硬度通常对于磨削刻面的任何指向变化都极为敏感。例如，图2所示为通过使八面体平面偏离示意图中所标出的（011）轴而得到的表面的材料切除的相对速率。叉形符号表示 A_x 方向上由磨削所导致的材料切除速率，圆形符号则表示 A_0 方向上的速率。我们看到在一个真正的八面体平面上， A_0 方向上的切除速率比 A_x 方向上的2倍还要大，但是只偏离 1° 就足以使相对硬度关系逆转。 英文

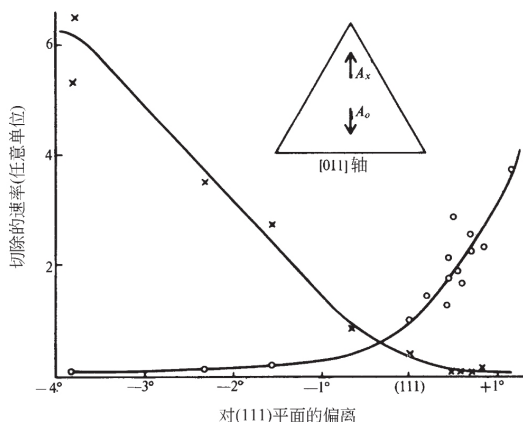


图2．在八面体平面附近的表面上碾磨所产生的材料切除的相对速率。符号 $\circ$ 和 $\times$ 对应于插图所示的方向。 英文

托尔考斯基的处理方法并未解释这种指向效应，他的方法在讨论八面体的面时也是有困难的。在立方体表面和十二面体面上的磨削速率差异可以利用通过在不同方向上磨削而导致不同结构产生的解理面的形貌来解释。由于解理面趋向于与一个八面体的面平行，这种处理方法似乎预言了一个不存在磨削难易方向的均一表面，而这与测量结果是违背的。为了解释这一点，我们必须考虑偏离的八面体刻面的行为。

如同图3A中颇为概略地显示的那样，通过机械切削过程抛光后得到的一个金刚石表面不是平坦的，而是包含着由解理面无规则排布所围成的峰和谷。由此可知，磨削是通过从这些微小山峰的顶部和侧部切除材料而实现的。如果图3A表示通过八面体的一个面的截面，平行于 A_x 和 A_0 方向，那么解理面就会具有这样的形貌：最有可能发生材料切除的位置是边 a 和 b （参考文献5）。还可以知道最容易磨削的方向是 A_0 ，以及大部分材料因此是从 b 边切除的。另一方面，如果令一个面与八面体的面倾斜成一个小角度，那么解理面的形貌仍保持原样，所以微小山峰的结构就如图3B中概略地显示的那样。从形貌的角度看，磨削轮一定会得到数量增加的 b 类型的边，而硬度则相应地下降。类似地，相反方向上的偏离则会增加硬度。

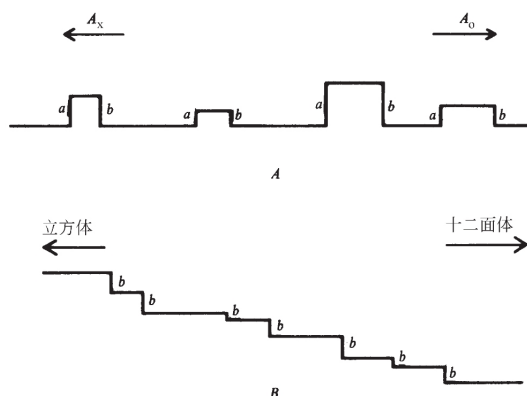


图3．抛光后金刚石表面的示意图（见正文）

我们还可以预期硬度随偏离的变化会非常快。如果微小山峰的线性尺度全都具有同样的数量级 h ，与磨削轮接触的山峰之间的平均距离就会大很多，因为真正的接触面积不到名义上的面积的 10^{-4} 。因此山峰之

间的距离可能具有 $100h$ 的数量级，才能使 1° 的偏离就足以使图3A中的形貌改变成图3B中那样，并由此而使易磨削位置的数目近似翻了一倍。类似的论证可以用来解释正的与倾斜的立方体面和十二面体面的硬度。从这个模型所能得到的所有预言都与实验结果吻合^[5]。 [英文](#)

我们还对磨削实验显示的抛光后金刚石表面的粗糙性质进行了研究，方法是观测在空气中金刚石在金刚石表面滑行时的摩擦力。一段时间之前，西尔^[7]曾指出抛光立方体表面的摩擦力随着滑行方位角的变化而变化，并具有四重对称性。最初看来这个结果是令人惊讶的，因为鲍登和汉威尔^[22]曾指出，空气中的金刚石表面为一层强烈吸附的薄膜所覆盖，它使摩擦力比起在高真空中清洁表面降了一个数量级。因此，即使金刚石表面被黏着性的吸附气体薄膜所覆盖，金刚石的对称性也会透过薄膜表现出来。 [英文](#)

空气中的金刚石间摩擦力是由鲍登和扬^[23]首先测得的，后来鲍登和泰伯指出，他们的结果表明摩擦力 μ 与负载 W 之间具有形如 $\mu \propto W^{-1/3}$ 的近似关联。接着，他们提出，这种关联性会由于实际上的真实接触区域之间的附着过程而增加，而且这种附着就是摩擦力产生的原因。不过，凯西和威尔克斯最近的测量结果^[25]表明，摩擦力在一个宽广的负载范围内是与负载无关的，其中包含着早期实验中的负载范围。于是，看起来附着机制并不是导致摩擦力产生的机制，这个结果被下面的事实所证实，即用轻油将金刚石表面润滑后摩擦力保持不变。 [英文](#)

利用与抛光的金刚石表面粗糙性质有关的粗糙度（或棘齿）型机制，很容易解释已观测到的摩擦力行为。也就是说，摩擦力缘起于承担着正常负载的两个金刚石表面在其凹凸部分越过彼此被迫分离时所需要的功。这些功的一部分会在粗糙且不规则的表面再次靠拢时转化为热，因为返回运动会倾向于不连续和不可逆。这种分离功与负载成比例，因此这种机制导致摩擦力数值与负载无关。我们相信这种机制更普遍地解释了空气中金刚石间的摩擦力，如同凯西和威尔克斯^[25]更为详细地讨论的那样。吸附膜承担润滑剂的作用，它减少了真空中所观测到的附着和强摩擦，但是并不掩盖表面的结构。 [英文](#)

图4a显示了最近关于金刚石在抛光立方表面上滑行的摩擦力的测量

结果，它与西尔的结果^[7]类似。金刚石的表面已经用常规方式进行了抛光，从而为平行于立方轴的一排精细的抛光线或者说凹槽所覆盖。尽管如此，摩擦还呈现出完全的四重对称性，在平行于和垂直于凹槽的方向上具有相同的数值。接着，我们在与立方轴成45°角的硬方向用磨削方法对一个表面进行重新抛光，直到原来的抛光线被一组与原方向成45°角的新抛光线所取代。曲线b显示了这个新表面上的摩擦力；摩擦力具有不同的数值，而且只呈现出二重对称性，最低数值出现在与抛光方向平行的方向上。

[英文](#)

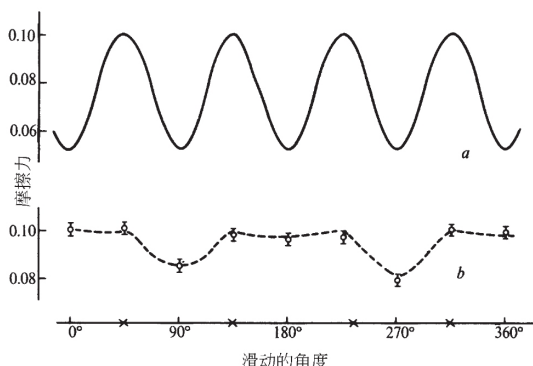


图4．金刚石在抛光的立方体表面滑动时的摩擦力作为方位角的函数。*a*，正常的软方向上的抛光后；*b*，硬方向上的抛光后。符号×表示立方轴的位置。

[英文](#)

上述结果证实，抛光表面的形貌是由机械切削所决定的。正如磨削过程在不同方向上以不同速率进行一样，由于解理面的取向，通过不同方向上的抛光所制得的表面就会有不同的结构。根据托尔考斯基所讨论的，在平行于立方轴的常规方向上抛光的表面会呈现为具有四重对称性的粗糙表面。但是，如果将金刚石在某一个硬方向上抛光，表面结构将会倾向于形成平行于抛光方向的凹槽，并具有摩擦力测量中所显示的二重对称性。目前我们还将研究扩展到观测用铁针反复划过同一表面区域时所涉及的磨损效应。

[英文](#)

第三组实验是利用高分辨电子显微技术和碳复型技术对抛光金刚石表面结构进行观测。研究表明该结构是不规则的并且具有很小的尺度；因此必须要特别小心以保证显微图像是清晰的而且没有受到像散的影响。图5显示了在类似条件下经谨慎控制所制备的显微图像，仅有的区别在于图5a的样品是云母的新鲜解理面，而图5b和5c则是抛光的金刚石

表面。金刚石显微图像中更为鲜明的对比说明其表面比云母要粗糙很多，而且其不规则性的尺度具有 $50\text{ \AA}$ 的数量级。 [英文](#)

图5b和5c中的显微图像是从同一块宝石以同样的技术得到的，不过图5b是来自以常规方式抛光的立方体表面，而图5c则是来自抛光的八面体表面。我们还曾在另一块金刚石立方体表面和八面体表面上观察到类似的结构，而且在十二面体表面上发现了不同的特征结构。这些结果确认了一个为金刚石抛光者所熟悉的事实，即抛光的质量取决于所抛光的特定的面，如同从抛光过程的机械性质中所得知的那样。人们期望至少在某种程度上表面结构可以用解理面来加以描述。在一个立方体表面上，这些解理面的交线会位于与抛光方向成 45° 角的方向，而且值得注意的是，在这些方向上存在着形貌特征。关于我们的结果的更多具体内容以及制样技术的细节，将会在其他文章中发表。 [英文](#)

金刚石的独特在于它外观上高度抛光的表面可能实际上在显微镜尺度下却是机械粗糙的，这是其脆性所导致的后果。由于金刚石的磨损速率和金属表面的光亮效果都高度依赖于工具的表面结构，因此目前我们正在将这些结果运用在将金刚石制成金属加工的切割工具上。例如，两个具有相同外部几何形状但是制作成具有不同结晶学取向的单晶金刚石车刀，其磨损速率表现为可重现的，而且相差7倍（参考文献26）。在这个特别的实验中，用两个结晶学取向完全不同的金刚石车刀车削一块用于制造汽车活塞的铝硅合金，其磨损几乎可以肯定是由上面所讨论的断裂面形貌所控制的。对于金刚石的磨损和它们所产生的光亮效果正进行进一步实验。 [英文](#)

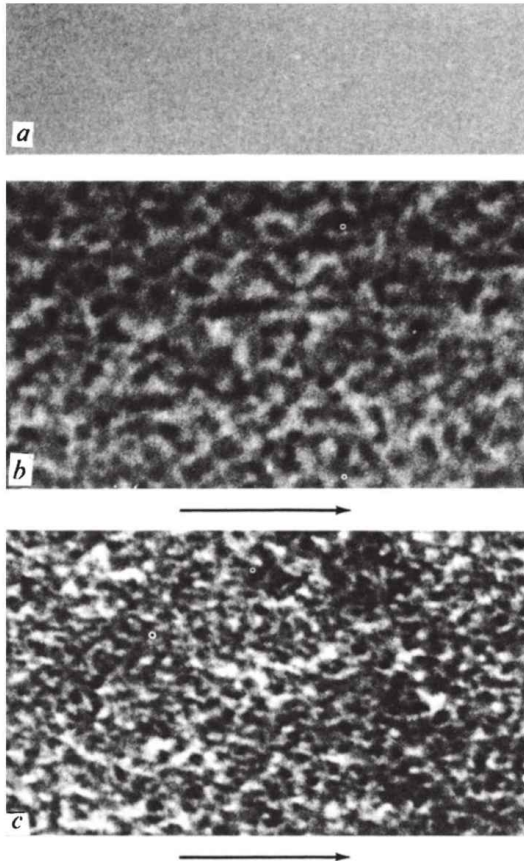


图5．样品的显微图像，*a*，取自解理的云母；*b*，取自抛光的金刚石立方表面；*c*，取自抛光的金刚石十二面体表面。箭头表示抛光方向。（ $\times 1,000,000$ ）。 [英文](#)

在此我要感谢凯西先生提供图1和图4，感谢威尔克斯博士提供图2，感谢德赖弗博士和桑顿先生提供图5中的显微图像，并且感谢科学研究理事会与戴比尔斯工业钻石部对这项研究的支持。 [英文](#)

（王耀杨 翻译；郝伟 审稿）

Black Hole Explosions?

S. W. Hawking

It was realized more than two hundred years ago that there is a critical mass and radius beyond which light cannot escape the gravitational field of an object—such an object becomes a “black hole”. This idea was rigorously validated by the theory of general relativity. Here Stephen Hawking shows that black holes have effective temperatures that are inversely related to their mass, and should therefore radiate photons and neutrinos from their event horizons—they are not fully “black”. As this radiation proceeds, the black hole loses mass. Finally it emits large quantities of X-rays and gamma-rays, and disappears in an explosion. “Hawking radiation” from black holes is now widely expected, but has not yet been seen. [中文](#)

QUANTUM gravitational effects are usually ignored in calculations of the formation and evolution of black holes. The justification for this is that the radius of curvature of space-time outside the event horizon is very large compared to the Planck length $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm, the length scale on which quantum fluctuations of the metric are expected to be of order unity. This means that the energy density of particles created by the gravitational field is small compared to the space-time curvature. Even though quantum effects may be small locally, they may still, however, add up to produce a significant effect over the lifetime of the Universe $\approx 10^{17}$ s which is very long compared to the

Planck time $\approx 10^{-43}$ s. The purpose of this letter is to show that this indeed may be the case: it seems that any black hole will create and emit particles such as neutrinos or photons at just the rate that one would expect if the black hole was a body with a temperature of $(\kappa/2\pi) (\hbar/2k) \approx 10^{-6} (M_\odot/M)K$ where κ is the surface gravity of the black hole¹. As a black hole emits this thermal radiation one would expect it to lose mass. This in turn would increase the surface gravity and so increase the rate of emission. The black hole would therefore have a finite life of the order of $10^{71} (M_\odot/M)^{-3}$ s. For a black hole of solar mass this is much longer than the age of the Universe. There might, however, be much smaller black holes which were formed by fluctuations in the early Universe². Any such black hole of mass less than 10^{15} g would have evaporated by now. Near the end of its life the rate of emission would be very high and about 10^{30} erg would be released in the last 0.1 s. This is a fairly small explosion by astronomical standards but it is equivalent to about 1 million 1 Mton hydrogen bombs. 中文

To see how this thermal emission arises, consider (for simplicity) a massless Hermitean scalar field ϕ which obeys the covariant wave equation $\phi;_{ab}g^{ab} = 0$ in an asymptotically flat space time containing a star which collapses to produce a black hole. The Heisenberg operator ϕ can be expressed as

$$\phi = \sum_i \{f_i a_i + \bar{f}_i a_i^+\}$$

where the f_i are a complete orthonormal family of complex valued solutions of the wave equation $f_{i;ab}g^{ab} = 0$ which are asymptotically ingoing and positive frequency—they contain only positive frequencies on past null infinity $I^{-3,4,5}$. The position-independent

operators a_i and a_i^+ are interpreted as annihilation and creation operators respectively for incoming scalar particles. Thus the initial vacuum state, the state containing no incoming scalar particles, is defined by $a_i|0_-\rangle = 0$ for all i . The operator ϕ can also be expressed

in terms of solutions which represent outgoing waves and waves crossing the event horizon:

$$\phi = \sum_i \{p_i b_i + \bar{p}_i b_i^+ + q_i c_i + \bar{q}_i c_i^+\}$$

where the p_i are solutions of the wave equation which are zero on the event horizon and are asymptotically outgoing, positive frequency waves (positive frequency on future null infinity I^+) and the q_i are solutions which contain no outgoing component (they are zero on I^+). For the present purposes it is not necessary that the q_i are positive frequency on the horizon even if that could be defined. Because fields of zero rest mass are completely determined by their values on I^- , the p_i and the q_i can be expressed as linear combinations of the f_i and the $\bar{f}_i$:

$$p_i = \sum_j \{\alpha_{ij} f_j + \beta_{ij} \bar{f}_j\} \text{ and so on}$$

The β_{ij} will not be zero because the time dependence of the metric during the collapse will cause a certain amount of mixing of positive and negative frequencies. Equating the two expressions for ϕ , one finds that the b_i , which are the annihilation operators for outgoing scalar particles, can be expressed as a linear combination of the ingoing annihilation and creation operators a_i and a_i^+

$$b_i = \sum_j \{\bar{\alpha}_{ij} a_j - \bar{\beta}_{ij} a_j^+\}$$

中文

Thus when there are no incoming particles the expectation value of the number operator $b_i^+ b_i$ of the i th outgoing state is

$$\langle 0 | b_i^+ b_i | 0 \rangle = \sum_j |\beta_{ij}|^2$$

中文

The number of particles created and emitted to infinity in a

gravitational collapse can therefore be determined by calculating the coefficients β_{ij} . Consider a simple example in which the collapse is spherically symmetric. The angular dependence of the solution of the wave equation can then be expressed in terms of the spherical harmonics Y_{lm} and the dependence on retarded or advanced time u, v can be taken to have the form $\omega^{-1/2} \exp(i\omega u)$ (here the continuum normalisation is used). Outgoing solutions $p_{lm\omega}$ will now be expressed as an integral over incoming fields with the same l and m :

$$p_{\omega} = \int \{ \alpha_{\omega\omega'} f_{\omega'} + \beta_{\omega\omega'} \bar{f}_{\omega'} \} d\omega'$$

(The lm suffixes have been dropped.) To calculate $\alpha_{\omega\omega'}$ and $\beta_{\omega\omega'}$ consider a wave which has a positive frequency ω on I^+ propagating backwards through spacetime with nothing crossing the event horizon. Part of this wave will be scattered by the curvature of the static Schwarzschild solution outside the black hole and will end up on I^- with the same frequency ω . This will give a $\delta(\omega-\omega')$ behaviour in $\alpha_{\omega\omega'}$. Another part of the wave will propagate backwards into the star, through the origin and out again onto I^- . These waves will have a very large blue shift and will reach I^- with asymptotic form

$$C\omega^{-1/2} \exp \{-i\omega K^{-1} \log(v_0 - v) + i\omega v\} \text{ for } v < v_0$$

and zero for $v \geq v_0$, where v_0 is the last advanced time at which a particle can leave I^- , pass through the origin and escape to I^+ . Taking Fourier transforms, one finds that for large ω' , $\alpha_{\omega\omega'}$ and $\beta_{\omega\omega'}$ have the form:

$$\alpha_{\omega\omega'} \approx C \exp[i(\omega - \omega')v_0](\omega'/\omega)^{1/2} \cdot \Gamma(1 - i\omega/K) [-i(\omega - \omega')]^{-1 + i\omega/K}$$

$$\beta_{\omega\omega'} \approx C \exp[i(\omega + \omega')v_0](\omega'/\omega)^{1/2} \cdot \Gamma(1 - i\omega/K) [-i(\omega + \omega')]^{-1 + i\omega/K}$$

The total number of outgoing particles created in the frequency range $\omega \rightarrow \omega + d\omega$ is $d\omega \int_0^\infty |\beta_{\omega\omega'}|^2 d\omega'$. From the above expression it can be seen that this is infinite. By considering outgoing wave packets which

are peaked at a frequency ω and at late retarded times one can see that this infinite number of particles corresponds to a steady rate of emission at late retarded times. One can estimate this rate in the following way. The part of the wave from I^+ which enters the star at late retarded times is almost the same as the part that would have crossed the past event horizon of the Schwarzschild solution had it existed. The probability flux in a wave packet peaked at ω is roughly

proportional to $\int_{\omega_1'}^{\omega_2'} \{ |\alpha_{\omega\omega'}|^2 - |\beta_{\omega\omega'}|^2 \} d\omega$ where $\omega_2' \gg \omega_1' \gg 0$. In the expressions given above for $\alpha_{\omega\omega'}$ and $\beta_{\omega\omega'}$ there is a logarithmic singularity in the factors $[-i(\omega-\omega')]^{-1+i\omega'/K}$ and $[-i(\omega+\omega')]^{-1+i\omega'/K}$. Value of the expressions on different sheets differ by factors of $\exp(2\pi n\omega/K)$. To obtain the correct ratio of $\alpha_{\omega\omega'}$ to $\beta_{\omega\omega'}$ one has to continue $[-i(\omega+\omega')]^{-1+i\omega'/K}$ in the upper half ω' plane round the singularity and then replace ω' by $-\omega'$. This means that, for large ω' ,

$$|\alpha_{\omega\omega'}| = \exp(\pi\omega/K) |\beta_{\omega\omega'}|$$

From this it follows that the number of particles emitted in this wave packet mode is $(\exp(2\pi\omega/K) - 1)^{-1}$ times the number of particles that would have been absorbed from a similar wave packet incident on the black hole from I^- . But this is just the relation between absorption and emission cross sections that one would expect from a body with a temperature in geometric units of $K/2\pi$. Similar results hold for massless fields of any integer spin. For half integer spin one again gets a similar result except that the emission cross section is $(\exp(2\pi\omega/K) + 1)^{-1}$ times the absorption cross section as one would expect for thermal emission of fermions. These results do not seem to depend on the assumption of exact spherical symmetry which merely simplifies the calculation. 中文

Beckenstein⁶ suggested on thermodynamic grounds that some multiple of K should be regarded as the temperature of a black hole. He did not, however, suggest that a black hole could emit particles as well as absorb them. For this reason Bardeen, Carter and I considered that the

thermodynamical similarity between κ and temperature was only an analogy. The present result seems to indicate, however, that there may be more to it than this. Of course this calculation ignores the back reaction of the particles on the metric, and quantum fluctuations on the metric. These might alter the picture. [中文](#)

Further details of this work will be published elsewhere. The author is very grateful to G. W. Gibbons for discussions and help. [中文](#)

(248, 30-31; 1974)

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Received January 17, 1974.

References:

1. Bardeen, J. M., Carter, B., and Hawking, S. W., *Commun. math. Phys.*, **31**, 161–170 (1973).
2. Hawking, S. W., *Mon. Not. R. astr. Soc.*, **152**, 75-78 (1971).
3. Penrose, R., in *Relativity, Groups and Topology* (edit. by de Witt, C. M., and de Witt, B. S). Les Houches Summer School, 1963 (Gordon and Breach, New York, 1964).
4. Hawking, S. W., and Ellis, G. F. R., *The Large-Scale Structure of Space-Time* (Cambridge University Press, London 1973).
5. Hawking, S. W., in *Black Holes* (edit. by de Witt, C. M., and de Witt, B. S), Les Houches Summer School, 1972 (Gordon and Breach, New York, 1973).
6. Beckenstein, J. D., *Phys. Rev.*, D7, 2333–2346 (1973).

黑洞爆炸？

霍金

人们在两百多年前就已经意识到，对于给定的半径有一个临界质量，当物体的质量超出临界质量时，其引力场就强到甚至连光都不能逃脱——这样的物体变成了“黑洞”。这一想法在广义相对论中得到了严格验证。本文中，斯蒂芬·霍金向我们表明黑洞有跟其质量成反比的等效温度，因此它必须从其事件视界向外辐射光子和中微子——即它们并不完全是“黑”的。黑洞在辐射过程中会损失质量，最终释放出大量的X射线和伽马射线，并在一次爆炸之后消失。虽然目前还没有直接观测到，但人们普遍相信黑洞存在“霍金辐射”。

英文

在计算黑洞的形成和演化时，一般可忽略量子引力效应。这一点的合理性在于，在事件视界外的时空曲率半径远大于普朗克长度 $(G\hbar/c^3)^{1/2} \approx 10^{-33}$ cm，而在此尺度上预期度规的量子涨落是1的量级。这意味着由引力场产生的粒子的能量密度和时空曲率相比要小。虽然量子效应在局部很小，然而它们仍然可能在宇宙的寿命 $\approx 10^{17}$ s内积累产生重大的影响，这个时间远长于普朗克时间 $\approx 10^{-43}$ s。这篇快报的目的是说明，似乎任何黑洞都将以预期的速率产生和发射粒子，如中微子或光子，正如同黑洞是一个温度为 $(\kappa/2\pi) (\hbar/2k) \approx 10^{-6} (M_{\odot}/M)K$ 的物体所表现的那样，其中 κ 是黑洞的表面引力^[1]。当黑洞发射这类热辐射时，我们预期它将损失质量。这本身将增大它的表面引力，因而增大其发射速率。从此，黑洞将具有 $10^{71}(M_{\odot}/M)^{-3}$ s量级的有限寿命。对于太阳质量的黑洞，这将比宇宙年龄更长。然而，可能存在许多较小的黑洞，它们是由早期宇宙中的涨落形成的^[2]。任何这类质量小于 10^{15} g的黑洞到现在都应该蒸发殆尽了。在接近它生命终了时，其粒子发射速率将非常高，在最后0.1s将释放约 10^{30} erg能量。以天文学的标准来看，这是一

个相当小的爆炸，但它相当于大约一百万个100万吨量级的氢弹爆炸。

英文

为了解释黑洞热辐射是如何产生的，为简单起见，在一个包含由一颗恒星塌缩形成的一个黑洞的渐近平直时空中，考虑一个无质量的厄米标量场 ϕ ，且它遵守协变波动方程 $\phi_{;ab}g^{ab} = 0$ 。海森堡算符 ϕ 可表示为：

$$\phi = \sum_i \{f_i a_i + \bar{f}_i a_i^+\}$$

其中， f_i 是波动方程 $f_{i;ab}g^{ab} = 0$ 的一族渐近向内、频率为正且完备正交归一复数解，它们在过去类光无穷远 I^- [3,4,5]只含有正频率。对于入射的标

量粒子，位置无关的算符 a_i 和 a_i^+ 分别解释为湮灭和产生算符。因此对于所有的 i ，初始真空态，即不含有向内传播的标量粒子的态，可定义为 $a_i |0\rangle = 0$ 。算符 ϕ 也可以用代表向外的波和穿过事件视界的波的解表示：

$$\phi = \sum_i \{p_i b_i + \bar{p}_i b_i^+ + q_i c_i + \bar{q}_i c_i^+\}$$

其中， p_i 是波动方程的解，它们在视界上为零且是渐近向外的正频波（在未来类光无穷远 I^+ 为正频率），而 q_i 是不含向外成分的解（它们在 I^+ 为零）。就现在的目的而言，即使可以被定义， q_i 在视界处也不一定是正频的。因为零静止质量的场完全被它们在 I^- 的值确定， p_i 和 q_i 可以表示为 f_i 和 $\bar{f}_i$ 的线性组合：

$$p_i = \sum_j \{\alpha_{ij} f_j + \beta_{ij} \bar{f}_j\} \text{ 等}$$

因为在塌缩期间度规的时间依赖性将导致一定量的正频和负频的混合，所以 β_{ij} 将不为零。令 ϕ 的两个表达式相等，可以发现向外传播标量粒子的湮灭算符 b_i 可以表示为向内湮灭和产生算符 a_i 和 a_i^+ 的线性叠加，即：

$$b_i = \sum_j \{\bar{\alpha}_{ij} a_j - \bar{\beta}_{ij} a_j^+\}$$

英文

于是在没有向内态的粒子时，第 i 个向外态的粒子数算符 $b_i^+ b_i$ 的期

望值为：

$$\langle 0 | b_i^\dagger b_i | 0 \rangle = \sum_j |\beta_{ij}|^2$$

英文

因此，在一次引力塌缩中产生并发射到无穷远的粒子的数目可以通过计算系数 β_{ij} 确定。考虑一个简单的例子，塌缩是球对称的。波动方程的解对角度的依赖可以用球谐函数 Y_{lm} 表示，对推迟或超前时间 u 、 v 的依赖可以取为 $\omega^{-1/2} \exp(i\omega u)$ （这里使用了连续归一化）。向外的解 $p_{lm\omega}$ 现在可以表示为对相同 l 和 m 的向内的场的积分：

$$p_\omega = \int \{ \alpha_{\omega\omega'} f_{\omega'} + \beta_{\omega\omega'} \bar{f}_{\omega'} \} d\omega'$$

这里略去了 lm 下标。为计算 $\alpha_{\omega\omega'}$ 和 $\beta_{\omega\omega'}$ ，考虑一个在 I^+ 为正频 ω ，在时空中反向传播的不穿过视界的波。这个波的一部分将被黑洞外的静态史瓦西解的曲率散射并将在 I^- 上以相同的频率 ω 终止。这将导致 $\alpha_{\omega\omega'}$ 的 $\delta(\omega-\omega')$ 行为。这个波的另外一部分将向后传播到恒星中，通过原点然后向外再到 I^- 。这些波将有非常大的蓝移，并将以渐近形式接近 I^- ：

$$C\omega^{-1/2} \exp \{-i\omega \kappa^{-1} \log(v_0 - v) + i\omega v\}, \text{ 当 } v < v_0 \text{ 时}$$

当 $v \geq v_0$ 时，这个蓝移值为0。其中， v_0 是最后的超前时间，此时的粒子尚可脱离 I^- ，通过原点并逃向 I^+ 。作傅里叶变换可以发现对于大的 ω' ， $\alpha_{\omega\omega'}$ 和 $\beta_{\omega\omega'}$ 有如下形式：

$$\alpha_{\omega\omega'} \approx C \exp[i(\omega - \omega')v_0](\omega'/\omega)^{1/2} \cdot \Gamma(1 - i\omega/\kappa) [-i(\omega - \omega')]^{-1 + i\omega/\kappa}$$

$$\beta_{\omega\omega'} \approx C \exp[i(\omega + \omega')v_0](\omega'/\omega)^{1/2} \cdot \Gamma(1 - i\omega/\kappa) [-i(\omega + \omega')]^{-1 + i\omega/\kappa}$$

在频率范围 $\omega \rightarrow \omega + d\omega$ 产生的向外粒子的总数为 $d\omega \int_0^\infty |\beta_{\omega\omega'}|^2 d\omega'$ ，并由上面的表达式可以看出这个量是无限的。通过考虑在较晚的推迟时间的、峰值频率 ω 的向外波包，可以看到这个无限的粒子数对应于较晚推迟时间的一个稳态发射率。可以通过以下方法估计这个发射率。波中来自 I^+ 的在较晚推迟时间进入恒星的部分（如果这部分存在的话）和穿过史瓦西解的过去视界的的部分几乎相同，峰值在 ω 处的波包中的概率流大致

正比于 $\int_{\omega_1'}^{\omega_2'} \{ |\alpha_{\omega\omega'}|^2 - |\beta_{\omega\omega'}|^2 \} d\omega$, 其中, $\omega_2' \gg \omega_1' \gg 0$ 。在上面给出的 $\alpha_{\omega\omega'}$ 和 $\beta_{\omega\omega'}$ 的表达式中, $[-i(\omega-\omega')]^{-1+i\omega'/K}$ 和 $[-i(\omega+\omega')]^{-1+i\omega'/K}$ 因子中有一个对数奇点。这个表达式在不同面上的值相差一个 $\exp(2\pi n\omega'K^{-1})$ 因子。为得到正确的 $\alpha_{\omega\omega'}$ 和 $\beta_{\omega\omega'}$ 的比值, 必须在上半 ω' 平面围绕奇点对 $[-i(\omega+\omega')]^{-1+i\omega'/K}$ 进行延拓并将 ω' 换为 $-\omega'$ 。这意味着对于大的 ω' :

$$|\alpha_{\omega\omega'}| = \exp(\pi\omega'/K) |\beta_{\omega\omega'}|$$

由此可得, 这个波包模式中发射的粒子数是从 I^- 入射到黑洞上的类似波包中已被吸收的粒子数的 $[\exp(2\pi\omega'/K)-1]^{-1}$ 倍, 但这正是根据几何单位下温度为 $K/2\pi$ 的物体所预期的吸收和发射截面之间的关系。类似结果对任何整数自旋的无质量场也同样成立。对半整数自旋, 正如我们对费米子的热辐射所预期的那样, 也能得到类似结果, 只是发射截面是吸收截面的 $[\exp(2\pi\omega'/K)+1]^{-1}$ 倍, 这些结果似乎并不依赖于只是为了简化计算而采取的精确球对称性假设。 [英文](#)

贝肯斯坦[6]在热力学基础上提出, K 的某个倍数应该被看作黑洞的温度。然而, 他并未提出, 黑洞可以像吸收粒子一样发射粒子。因此, 巴丁、卡特和我曾经认为, K 和温度之间的热力学的相似性只是一种类比。然而, 目前的结果似乎表明, 可能存在比这更多的内容。当然, 这个计算忽略了粒子对度规的反作用以及度规本身的量子涨落, 这些不排除会改变这个物理图像。 [英文](#)

这项工作的进一步细节将在其他地方发表。作者非常感谢吉本斯给予的建议和帮助。 [英文](#)

(沈乃澍 翻译; 肖伟科 审稿)

Observation of Cold Nuclear Fusion in Condensed Matter

S. E. Jones *et al.*

In 1989, two groups of researchers working in Utah believed they had found evidence that electrolysis of heavy water using palladium electrodes could trigger nuclear fusion of the deuterium atoms, offering vast amounts of energy in a simple benchtop process. Both groups submitted their results to *Nature*. After questions raised by referees, one team—Martin Fleischmann, Stanley Pons and their student Marvin Hawkins at the University of Utah—withdrawed their paper and published it elsewhere. This is the other paper, by Steven Jones and colleagues at Brigham Young University. The controversial claim of cold fusion spurred worldwide activity to replicate the results, but no such vindication was ever found, and electrolytic “cold fusion” is now almost universally discredited. [中文](#)

When a current is passed through palladium or titanium electrodes immersed in an electrolyte of deuterated water and various metal salts, a small but significant flux of neutrons is detected. Fusion of deuterons within the metal lattice may be the explanation. [中文](#)

FUSION of the nuclei of isotopes of hydrogen is the principal means of energy production in the high-temperature interiors of stars. In

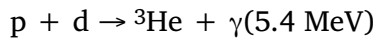
relatively cold terrestrial conditions, the nuclei are surrounded by electrons and can approach one another no more closely than is allowed by the molecular Coulomb barrier. The rate of nuclear fusion in molecular hydrogen is then governed by quantum-mechanical tunnelling through that barrier, or equivalently, the probability of finding the two nuclei at zero separation. In a deuterium molecule, where the equilibrium separation between deuterons (d) is $0.74 \text{ \AA}$, the d-d fusion rate is exceedingly slow, about 10^{-74} per D_2 molecule per second¹. [中文](#)

By replacing the electron in a hydrogen molecular ion with a more massive charged particle, the fusion rate is greatly increased. In muon-catalysed fusion, the internuclear separation is reduced by a factor of ~ 200 (the ratio of the muon to electron mass), and the nuclear fusion rate correspondingly increases by about eighty orders of magnitude. Muon-catalysed fusion has been shown to be an effective means of rapidly inducing fusion reactions in low-temperature mixtures of hydrogen isotopes^{2,3}. [中文](#)

A hypothetical quasi-particle a few times as massive as the electron would increase the cold fusion rate to readily measurable levels of $\sim 10^{-20}$ fusions per d-d molecule per second¹. The results reported here imply that a comparable distortion of the internuclear wavefunction can be realized when hydrogen isotope nuclei are loaded into metals under certain conditions. We have discovered a means of inducing nuclear fusion without the use of either high temperatures or radioactive muons. [中文](#)

Indirect Evidence

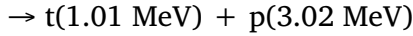
Observations of naturally occurring ^3He in the Earth suggested to us new directions for laboratory investigations of nuclear fusion in condensed matter. ^3He is produced by the following fusion reactions:



(1)



(2a)



(2b)

Tritium (t) decays with a 12.4-yr half-life to produce ${}^3\text{He}$. The well established high ${}^3\text{He}/{}^4\text{He}$ ratio in solids, liquids and gases associated with volcanoes and other areas of high heat flow⁴⁻⁶ suggests fusion as a possible source for the ${}^3\text{He}$. [中文](#)

To estimate a possible rate of fusion in the Earth, we assume a simple, steady-state model in which the known flux of ${}^3\text{He}$ out of the mantle, 2×10^{19} ${}^3\text{He}$ atoms per second⁷, arises from p-d fusion occurring uniformly in the mantle water reservoir, taken as $\sim 1.4 \times 10^{24}$ g(R. Poreda, personal communication). Note that if the Earth contains “primordial” ${}^3\text{He}$, our calculated rate will be an upper limit; on the other hand, if fusion-produced ${}^3\text{He}$ is stored in the mantle (so that the outward flux does not equal the production rate), our value will be a lower limit. As each p-d fusion produces one ${}^3\text{He}$ atom, and as the isotopic abundance of deuterium in water is $\sim 1.5 \times 10^{-4}$ deuterons per proton, we infer a geological fusion rate constant, λ_f , of

$$\begin{aligned} \lambda_f &\approx \frac{2 \times 10^{19} {}^3\text{He atoms s}^{-1}}{1.4 \times 10^{43} \text{ deuterons}} \\ &\approx 10^{-24} \text{ fusions d}^{-1} \text{ s}^{-1} \end{aligned} \quad (3)$$

This rate is fifty orders of magnitude larger than that expected in an isolated HD molecule, and fusion at this rate could be detected if reproduced in the laboratory. [中文](#)

Cold nuclear fusion may be important in celestial bodies other than the Earth. Jupiter, for example, radiates about twice as much heat as it receives from the Sun. It is interesting to consider whether cold nuclear fusion in the core of Jupiter, which is probably metallic hydrogen plus iron silicate, could account for its excess heat. Heat is radiated at an approximate rate of 10^{18} watts, which could be produced by p-d fusions occurring at a rate of 10^{30} s^{-1} . Assuming a core of radius $4.6 \times 10^9 \text{ cm}$, containing mostly hydrogen, with density $\sim 10 \text{ g cm}^{-3}$ and a deuteron/proton ratio of $\sim 10^{-4}$, we deduce a required p-d fusion rate of $\gamma_f \approx 10^{-19} \text{ fusions d}^{-1} \text{ s}^{-1}$ if all the heat derives from fusion. Catalysed nuclear fusion at this rate could be readily measured in the laboratory. [中文](#)

Further evidence for cold nuclear fusion in condensed matter comes from studies of ^3He and ^4He in metals. There have been several reports of high ^3He concentrations in metal crucibles and foils (H. Craig, R. Poreda, A. Nier, personal communications), consistent with *in situ* formation by cold fusion. In particular, Mamyrin *et al.*⁸ report the occurrence of patchy, high concentrations of ^3He in a number of metal foils. Electrolytic refining of the metals could have provided the appropriate conditions for the cold nuclear fusion reactions (1) and possibly (2). Among several possible explanations for the observations, the authors suggest an analogue of muon catalysis⁸. [中文](#)

Detection of Cold-fusion Neutrons

The considerations outlined above led to laboratory experiments performed at Brigham Young University to determine whether cold nuclear fusion can actually occur in condensed matter. We now report the observation of deuteron-deuteron fusion at room temperature during low-voltage electrolytic infusion of deuterons into metallic titanium or palladium electrodes. The fusion reaction (2a) is apparently catalysed by the deposition of d^+ and metal ions from the electrolyte at (and into) the negative electrode. Neutrons with an

energy of ~ 2.5 MeV are clearly detected with a sensitive neutron spectrometer. The experimental layout is shown in Fig. 1. 中文

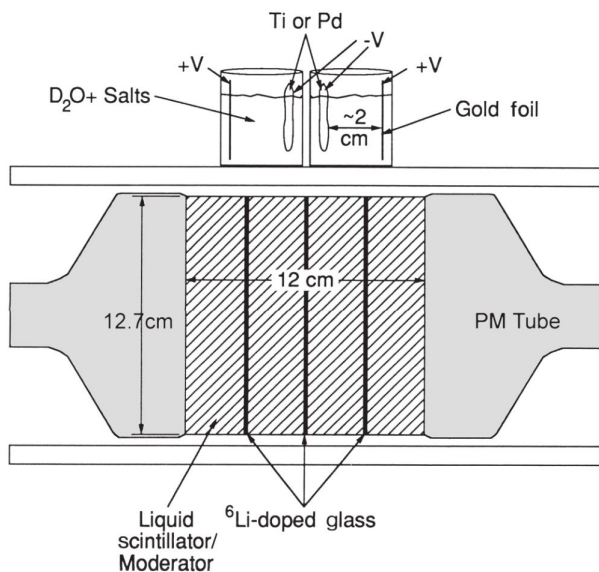


Fig. 1. Schematic diagram of the experiment. Electrolytic cells are shown on top of the neutron spectrometer. 中文

The neutron spectrometer, developed at Brigham Young University over the past few years (ref. 9 and manuscript in preparation) has been crucial to the identification of this cold fusion process. The detector consists of a liquid organic scintillator (BC-505) contained in a glass cylinder 12.5 cm in diameter, in which three glass scintillator plates doped with lithium-6 are embedded. Neutrons deposit energy in the liquid scintillator through multiple collisions, and the resulting light output yields energy information. As their energy decreases, the neutrons are scavenged by ${}^6\text{Li}$ nuclei, and the reaction $n + {}^6\text{Li} \rightarrow t + {}^4\text{He}$ results in scintillations in the glass. Pulse shapes and amplitudes from the two scintillators differ; the two distinct signals are registered by two photomultiplier tubes, whose signals are summed. A coincidence of identified signals from the two media within $20 \mu\text{s}$ identifies an incoming neutron that has stopped in the detector. 中文

The spectrometer was calibrated using 2.9- and 5.2-MeV neutrons generated by deuteron–deuteron interactions at 90° and 0°, respectively, with respect to a deuteron beam from a Van de Graaff accelerator. The observed energy spectra show broad structures which imply that 2.45-MeV neutrons should appear in the multichannel analyser spectrum in channels 45-150. The stability of the detector system was checked between data runs by measuring the counting rate for fission neutrons from a broad-spectrum californium-252 source. [中文](#)

We have performed extensive tests to verify that the neutron spectrometer does not respond preferentially in this pulse height range to other sources of radiation such as thermal neutrons. In particular, we made unsuccessful efforts to generate false 2.5-MeV neutron “signals” by using various γ -ray and neutron sources and by turning auxiliary equipment on and off. Neutron-producing machines such as the Van de Graaff accelerators were off during all foreground and background runs. [中文](#)

Many background runs were made using operating cells (described below) containing standard electrodes and electrolytes, except that H₂O replaced the D₂O; other background runs were made using both new and previously used standard cells containing D₂O plus the usual electrolyte but with no electrical current. The individual background runs were all featureless and closely followed the pattern of the integrated background shown in Fig. 2. Background rates in the neutron counter are $\sim 10^{-3} \text{ s}^{-1}$ in the energy region where 2.5-MeV neutrons are anticipated. By comparing energy spectra from γ -ray and neutron sources we have determined that approximately one-fourth of the observed background events arise from accidental coincidences of γ -rays and three-fourths from ambient neutrons. The γ -ray background comes mainly from radioactive radium and potassium in the surrounding materials. We attribute the ambient neutrons to cosmic-

ray sources. Although the typical neutron evaporation spectrum (at birth) has a broad maximum near 2.5 MeV (ref. 10), Monte Carlo calculations show that moderation in the source medium (predominantly the shielding surrounding the detector) will wash out this structure and produce a smoothly decreasing background spectrum above 0.5 MeV, as observed. [中文](#)

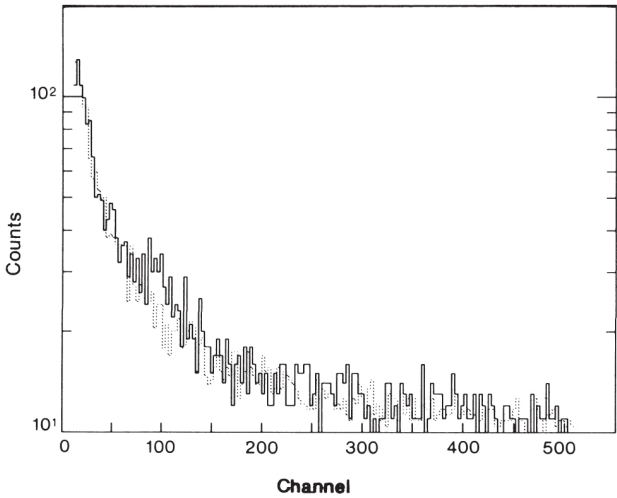


Fig. 2. Foreground (solid) and background (dashed) counts as a function of pulse height (corresponding to neutron energy) in the neutron spectrometer. Ten counts have been added to each three-channel bin for clarity of presentation. [中文](#)

The predicted and measured absence of structure in the spectrum of cosmic-ray-produced neutrons will not be influenced by the relatively small temporal variations that may occur in the cosmic-ray flux, such as the observed decreases that may accompany solar flares. This means that the observed peak at 2.5 MeV cannot be accounted for by ambient-neutron background variations, because, as explained below, the analysis is based on the shape of the spectra and not simply on rates. Low-energy cosmic-ray muons would be rapidly scavenged by nuclei with high atomic number, so as to reduce muon-catalysed d-dfusion to a negligible level^{2,3}. Considering volume and solid angle, the rate of production of neutrons by muons absorbed by carbon nuclei in the detector exceeds that from muons absorbed by oxygen nuclei in the electrolytic cells by a factor of ~ 60 . Thus, the presence

or absence of electrolytic cells is an unimportant perturbation in the background. [中文](#)

During the search for suitable catalytic materials, the following (unoptimized) prescription for the electrolytic cells evolved. It began with salts typical of volcanic hot springs and included electrode-metal ions. The electrolyte is typically a mixture of ~ 160 g D_2O plus various metal salts in ~ 0.1 g amounts each: $FeSO_4 \cdot 7H_2O$, $NiCl_2 \cdot 6H_2O$, $PdCl_2$, $CaCO_3$, $Li_2SO_4 \cdot H_2O$, $Na_2SO_4 \cdot 10H_2O$, $CaH_4(PO_4)_2 \cdot H_2O$, $TiOSO_4 \cdot H_2SO_4 \cdot 8H_2O$, and a very small amount of $AuCN$. The pH is adjusted to $\lesssim 3$ with HNO_3 . All 14 runs reported here began with this basic electrolyte. [中文](#)

Titanium and palladium, initially selected because of their large capacities for holding hydrogen and forming hydrides, were found to be effective negative electrodes. Individual electrodes consisted of ~ 1 g purified “fused” titanium in pellet form, or 0.05 g of 0.025-mm-thick palladium foils, or 5 g of mossy palladium. Typically 4–8 cells were used simultaneously. The palladium pieces were sometimes re-used after cleaning and roughening the surfaces with dilute acid or abrasives. Hydrogen bubbles were observed to form on the Pd foils only after several minutes of electrolysis, suggesting the rapid absorption of deuterons into the foil; oxygen bubbles formed at the anode immediately. Gold foil was used for the positive electrodes. Direct-current power supplies provided 3–25 volts across each cell at currents of 10–500 mA. Correlations between fusion yield and voltage, current density, or surface characteristics of the metallic cathode have not yet been established. [中文](#)

Small jars, ~ 4 cm high and 4 cm in diameter, held ~ 20 ml of electrolyte solution each. The electrolytic cells were placed on or alongside the neutron counter, as shown in Fig. 1. The present cells are simple and undoubtedly far from optimum. Nevertheless, the present combination of our cells with the neutron spectrometer is sufficient to

establish the phenomenon of cold nuclear fusion during electrolytic infusion of deuterium into metals. [中文](#)

Figure 2 shows the energy spectrum obtained under the conditions described above, juxtaposed with the (scaled) background spectrum. We acquired about twice as much background data as foreground data. Assuming conservatively that all deviations from background are statistical fluctuations, we scale the background counts by a factor of 0.46 to match the total number of foreground counts over the entire energy range shown in Fig. 2. A feature in channels 45–150 rises above background by nearly four standard deviations. This implies that our assumption is too conservative and that this structure represents a real physical effect. After re-scaling the background by a factor of 0.44 to match the foreground levels in regions just below and just above this feature, the difference plot (Fig. 3) is obtained. It shows a robust signal centred near channel 100, with a statistical significance of almost five standard deviations. A gaussian fit to this peak yields a centroid at channel 101 with a standard deviation of 28 channels, and an amplitude of 23.2 ± 4.5 counts. Both the position and width of this feature correspond to those expected for 2.5-MeV neutrons, according to the spectrometer calibration. The fact that a significant signal appears above background with the correct energy for d–d fusion neutrons (~ 2.5 MeV) provides strong evidence that room-temperature nuclear fusion is occurring at a low rate in the electrolytic catalysis cells. [中文](#)

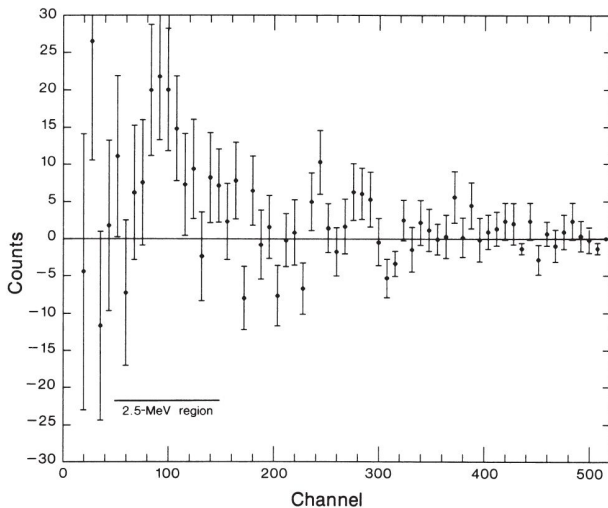


Fig. 3. Difference spectrum obtained by subtracting scaled background from the foreground. Statistical errors ($\pm 1\sigma$) are shown for each eight-channel bin. [中文](#)

Fusion Rate Determination

It is instructive to examine the fourteen individual runs which enter into the combined data discussed above. These runs were performed over the period 31 December 1988 to 6 March 1989. Figure 4 displays, for each run, the ratio of foreground count rate in the 2.5-MeV energy region to the background rate obtained for each run. Electronic changes were made in the apparatus during the course of the experiment which altered the observed background rates, so we plot the data in terms of foreground-to-background ratios rather than absolute rates. In one set of data (runs 1 to 8) for which the system was kept as untouched as possible to avoid changes in background rates, the measured rate of detection of 2.5-MeV neutrons was $(6.2 \pm 1.3) \times 10^{-4} \text{ s}^{-1}$ above background. For this set of data, the background and foreground rates for all energies above $\sim 3 \text{ MeV}$ (that is, for all channels from 190 to 512) are equal, at $(1.4 \pm 0.1) \times 10^{-3} \text{ s}^{-1}$.

[中文](#)

Run 6 is particularly noteworthy, with a statistical significance of approximately five standard deviations above background. Fused

titanium pellets were used as the negative electrode, with a total mass of ~ 3 g. The neutron production rate increased after about one hour of electrolysis. After about eight hours, the rate dropped dramatically, as shown in the follow-on run 7. At this time, the surfaces of the titanium electrodes showed a dark grey coating. An analysis using electron microscopy with a microprobe showed that the surface coating was mostly iron, deposited with deuterons at the cathode. The same phenomenon of a decrease in the neutron signal after about eight hours of operation appears in run 13 followed by run 14. Runs 13 and 14 use the same eight electrochemical cells, and again the negative electrodes developed coatings after a few hours of electrolysis. These observations suggest the importance of surface conditions for the cold fusion process. Variations in surface conditions and electrolyte composition are anticipated during each test run because materials plate out of solution; the solution pH also changes significantly during a run. These 14 runs represent two choices of electrode material plus various operating currents. These variations may account for the fluctuations in the signal level that are evident in Fig. 4. As these runs represent a total of only ~ 200 signal neutrons at an average rate of ~ 2 per hour, it was difficult to optimize experimental conditions. This is a task for future research. 中文

The observed “turning off” of the signal after about eight hours may account for low signal-to-background ratios in runs 1 and 3, in that a signal that lasted for only a few hours may have been overwhelmed after a long (~ 20 -hour) running time. When run 10 started with rates substantially above background, we stopped the run and removed half of the electrochemical cells as a test. The neutron production rate dropped off as expected (run 11). In determining the statistical significance of the data, we included runs 1, 3, 7, 11 and 14, even though we see a systematic reason for their low foreground-to-background ratios as explained above. Run 8, shown in Fig. 4, was inadvertently lost from the magnetic storage device and could not be

included in Figs 2 and 3. This does not change our conclusions.

中

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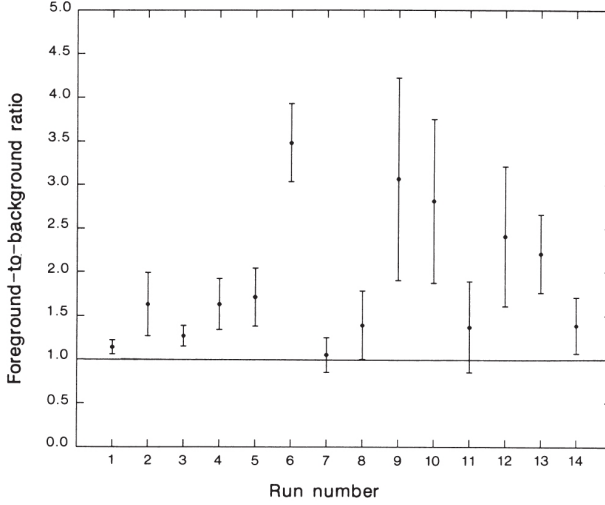


Fig. 4. Ratio of foreground rate to background rate for each run, in the 2.5-MeV energy region of the pulse-height spectrum. Statistical errors ($\pm 1\sigma$) are shown.

中文

We can estimate the rate for the neutron-production branch of d-d fusion during electrolysis, specifically for run 6, as follows:

$$\text{Fusions per deuteron pair per second} = \frac{R / \varepsilon}{M \times \frac{d}{2M}} \quad (4)$$

where the observed rate of neutron detection, $R = (4.1 \pm 0.8) \times 10^{-3} \text{ s}^{-1}$, is based on foreground minus corresponding background counts in channels 45–150; the neutron detection efficiency, including geometrical acceptance, is calculated using a Monte Carlo neutron-photon transport code¹¹ to be $\varepsilon = (1.0 \pm 0.3)\%$; $M \approx 4 \times 10^{22}$ titanium atoms for 3 g of titanium; and the ratio of deuteron pairs to metal ions, $d/2M \approx 1$, is based on the assumption that nearly all tetrahedral sites in the titanium lattice are occupied, forming the γ -TiD₂ hydride. Then the estimated cold nuclear fusion rate for the neutron-production branch, by equation (4), is $\lambda_f \approx 10^{-23}$ fusions per deuteron pair per second. If most fusions take place near the surface, or if the titanium lattice is far from saturated with deuterons, or if

conditions favouring fusion occur intermittently, then the inferred fusion rate must be much larger, perhaps 10^{-20} fusions per deuteron pair per second. [中文](#)

We note that such a fusion rate could be achieved by “squeezing” the deuterons to about half their normal ($0.74\text{-}\text{\AA}$) separation in molecules. That such rates are now observed in condensed matter suggests catalysed “piezonuclear” fusion as the explanation¹. A possible cause is that quasi-electrons form in the deuterated metal lattice, with an effective mass a few times that of a free electron. Isotopes of hydrogen are known to accumulate at imperfections in metal lattices¹², and a local high concentration of hydrogen ions might be conducive to piezonuclear fusion. Because we have not seen any evidence for fusion in equilibrated, deuterated metals or compounds such as methylamine- d_2 deuteriochloride or ammonium- d_4 chloride, we conclude that non-equilibrium conditions are essential. Electrolysis is one way to produce conditions that are far from equilibrium. [中文](#)

It may seem remarkable that one might influence the effective rate of fusion by varying external parameters such as pressure, temperature and electromagnetic fields, but just such effects are seen in another form of cold nuclear fusion, muon-catalysed fusion¹³. [中文](#)

Conclusions

The correlation of ideas regarding cold piezonuclear fusion¹ with observations of excess ^3He in metals and in geothermal areas of the Earth led to our experimental studies of fusion in electrochemical cells, which began in May 1986. Our electrolyte compositions evolved from geochemical considerations, and changed as results were observed. The presence of a fusion neutron signal was consistently reproduced, although the rate varied widely. Now that our exploratory searches have disclosed a small piezonuclear fusion effect, it remains to disentangle the factors that influence the fusion rate.

The need for off-equilibrium conditions is clearly implied by our data, and suggests that techniques other than electrochemistry may also be successful. We have begun to explore the use of ion implantation and of elevated pressures and temperatures, mimicking geological conditions. Cold nuclear fusion in condensed matter may be of interest as a novel probe of metal-hydrogen systems, including geological ones, and as a source of monoenergetic neutrons. If deuterium-deuteron fusion can be catalysed, then the d-t fusion reaction is possibly favoured because of its much larger nuclear cross-section. Although the fusion rates observed so far are small, the discovery of cold nuclear fusion in condensed matter opens the possibility, at least, of a new path to fusion energy. 中文

(338, 737-740; 1989)

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Received 24 March; accepted 14 April 1989.

References:

1. Van Siclen, C. D. & Jones, S. E. *J. Phys. G.* **12**, 213-221 (1986).
2. Jones, S. E. *Nature* **321**, 127-133 (1986).
3. Rafelski, J. & Jones, S. E. *Scient. Am.* **257**, 84-89 (July 1987).
4. Craig, H., Lupton, J. E., Welhan, J. A. & Poreda, R. *Geophys. Res. Lett.* **5**, 897-900 (1978).
5. Lupton, J. E. & Craig, H. *Science* **214**, 13-18 (1981).
6. Mamyrin, B. A. & Tolstikhin, L. N. *Helium Isotopes in Nature* (Elsevier, Amsterdam, 1984).
7. Craig, H. & Lupton, J. E. in *The Sea* Vol. 7 (ed. Emiliani, C.) Ch. 11 (Wiley, New York, 1981).
8. Mamyrin, B. A., Khabarin, L. V. & Yudenich, V. S. *Soviet Phys. Dokl.* **23**, 581-583 (1978).
9. Jensen, G. L., Dixon, D. R., Bruening, K. & Czirr, J. B. *Nucl. Instrum. Meth.* **220**, 406-408 (1984).
10. Hess, W. N., Patterson, H. W. & Wallace, R. *Phys. Rev.* **116**, 445-457 (1959).
11. MCNP: Monte Carlo Neutron and Photon Transport Code, CCC-200 (Version 3) (Radiation Shielding Information Center, Oak Ridge Natn. Lab., 1983).

12. Bowman, R. C. Jr in *Metal Hydrides* (ed. Bambakides, G.) 109-144 (Plenum, New York, 1981).
13. Jones, S. E. *et al. Phys. Rev. Lett.* **51**, 1757-1760 (1983).

Acknowledgements. We acknowledge valuable contributions of James Baer, David Mince, Rodney Price, Lawrence Rees, Eugene Sheely and J. C. Wang of Brigham Young University, and of Mike Danos, Fraser Goff, Berndt Müller, Albert Nier, Göte Ostlund and Clinton Van Siclen. We especially thank Alan Anderson for advice on the data analysis and Harmon Craig for continuing encouragement. This research is supported by the Advanced Energy Projects Division of the US Department of Energy.

凝聚态物质中观察到的冷核聚变

琼斯等

1989年，犹他州的两个研究小组认为他们已经找到了证据证明，在一个简单的桌面装置中，用钽电极电解重水会引发氘原子核聚变，释放巨大的能量。这两组都把他们的结果投到了《自然》。在审稿人提出问题之后，其中的一组——犹他大学的马丁·弗莱施曼，斯坦利·庞斯和他们的学生马尔温·霍金斯——撤回了他们的论文并在别处发表。本文则是另一篇论文，由杨百翰大学的史蒂文·琼斯及其同事们所作。冷核聚变的提出颇具争议，激励着世界范围内的研究行动来重复该结果，但是一直没有得到证实，如今，由电解产生的“冷核聚变”受到人们的普遍质疑。 [英文](#)

当电流通过浸没在由氘化水和各种金属盐组成的电解质中的钽或钽电极时，我们探测到了一个微弱却意义重大的中子流。对于该现象，金属晶格中的氘核聚变或许可以做出解释。 [英文](#)

在高温的恒星内部，氢同位素的核聚变是能量产生的主要途径。而在相对寒冷的陆地环境中，原子核被电子包围着，并且彼此间的距离不会比分子库仑势垒所允许的距离更小。因此，氢气分子的核聚变率受穿过势垒的量子力学隧道效应的控制，相当于受两核间距为零的现象发生概率的控制。在氘分子中，氘核（即d）间的平衡距离为 $0.74 \text{ \AA}$ ，d-d聚变率非常小，大约每秒钟每个氘气分子中发生 10^{-74} 次聚变^[1]。 [英文](#)

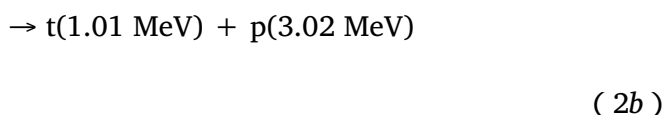
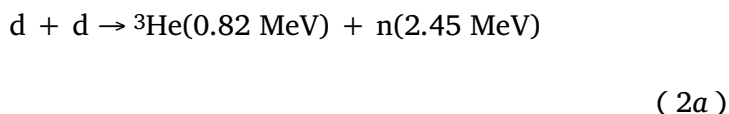
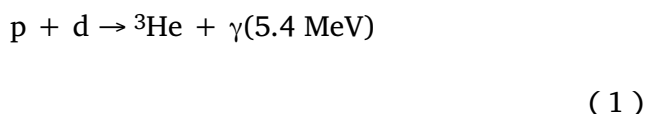
用一个更大的带电粒子来替代氢分子离子中的电子，聚变率会大大提高。在 μ 子催化聚变中，核间距会缩小约200倍（即 μ 子与电子质量之

比)，相应地核聚变率也会提升约80个数量级。 μ 子催化聚变已经被证实为能够在氢同位素低温混合物中迅速引起聚变反应的一个有效途径[2,3]。[英文](#)

一个假定的比电子大几倍的准粒子会将冷核聚变率增加到易于测量到的水平，即每秒钟每个氘核对中约 10^{-20} 次聚变^[1]。本文报告的结果表明，在特定条件下将氢同位素原子核注入金属中，可以实现原子核间波函数相应的变化。我们已经发现了一种在既不要求高温也不使用放射性 μ 子的情况下实现核聚变的方法。[英文](#)

间接证据

对地球上自然产生的 ^3He 的观测，为我们在实验室条件下研究凝聚态物质中的核聚变指明了新的方向。 ^3He 在下列聚变反应中产生：



氚（即t）以12.4年的半衰期衰变产生 ^3He 。与火山爆发和其他高温热流相关的固体、液体、气体中存在的已经确定的 $^3\text{He}/^4\text{He}$ 的高比值^[4-6]表明，聚变是 ^3He 的一个可能来源。[英文](#)

为估算地球中的可能聚变率，我们假设一个简单的稳态模型，在该模型中，已知从地幔中流出的 ^3He 流为每秒钟 2×10^{19} 个 ^3He 原子^[7]，是由在地幔储水层（约 $1.4 \times 10^{24} \text{ g}$ ）中均匀发生的p-d聚变引起的（波雷达，个人交流）。需要注意的是，一方面，如果地球含有“原始” ^3He ，那么我们计算出的上述聚变率就是上限；另一方面，如果核聚变产生的 ^3He 是储藏在地幔中的（这样一来，向外流出的量就与产生率不相

等)，那么我们的计算值就是下限。由于每次p-d聚变产生一个 ^3He 原子且水中氘的同位素丰度约为每个质子对应 1.5×10^{-4} 个氘核，我们推断出一个地球的聚变率常数 λ_f ：

$$\begin{aligned}\lambda_f &\approx \frac{2 \times 10^{19} \text{ } ^3\text{He 原子/秒}}{1.4 \times 10^{43} \text{ 氘核}} \\ &\approx 10^{-24} \text{ 聚变 / (氘核} \cdot \text{秒)}\end{aligned}\quad (3)$$

这个聚变率要比孤立HD分子中的预期聚变率高出50个数量级，如果在实验室条件下重现该过程，处于这种聚变率的聚变是可以被探测到的。

英文

与地球不同，天体中的冷核聚变或许是很重要的。例如木星，它辐射出的热量大约是其从太阳那里吸收的热量的两倍。那么，发生在可能由金属氢加铁硅酸盐组成的木星核心处的冷核聚变能否为多余的热量做出解释呢？这是一个很有趣的问题。热量辐射率大约为 10^{18} W ，而该热量可以由聚变率为 10^{30} s^{-1} 的p-d聚变产生^[1]。假设有这样一个核心，其半径为 $4.6 \times 10^9 \text{ cm}$ ，主要由氢组成，密度约为 $10 \text{ g} \cdot \text{cm}^{-3}$ ，氘核与质子之比约为 10^{-4} ，且如果所有的热量全部来自聚变，那么我们推断出p-d聚变率 λ_f 必须为每秒钟每个氘核中约 10^{-19} 次聚变。处于这个聚变率的催化核聚变在实验室条件下可以很容易地被探测到。

英文

关于凝聚态物质中冷核聚变的进一步证据来源于对金属中的 ^3He 和 ^4He 的研究。目前已经有一些关于金属坩埚和金属箔中的高浓度 ^3He 的报道（克雷格，波雷达，尼尔，个人交流），且与冷核聚变在原位形成相一致。特别是，马梅林等人声称在许多金属箔中观察到了分布不均匀的高浓度 ^3He ^[8]。金属的电解精炼可能为冷核聚变反应（1），甚至可能包括反应（2）提供了适宜的条件。在对该现象的一些可能的解释中，作者比较赞同类似于 μ 子的催化作用的解释^[8]。

英文

冷核聚变中子的探测

鉴于上面概述的种种考虑，在杨百翰大学进行了实验以验证冷核聚变能否在凝聚态物质中发生。我们在这里报道了室温下将氘核向金属钛或钨电极低压电解注入期间的d-d聚变。聚变反应（2a）显然受到了负

电极处（及其内部）电解质中的d⁺和金属离子沉积的催化。灵敏的中子谱仪也明显探测到能量约为2.5 MeV的中子。实验装置如图1所示。

英文

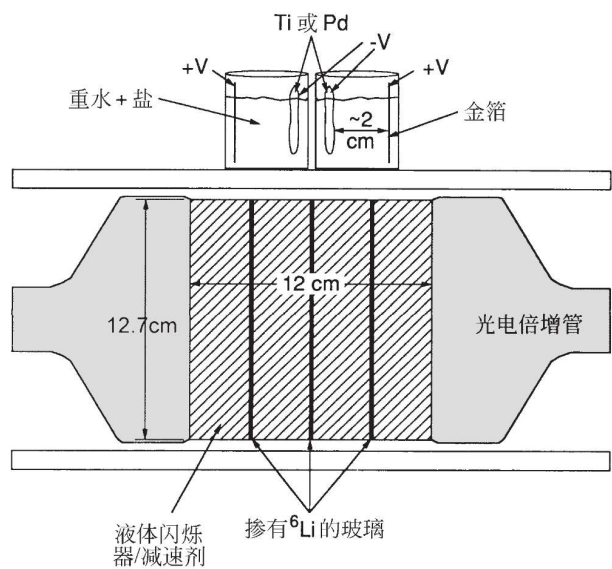


图1 . 实验装置简图。在中子谱仪上放置的是电解池。 英文

杨百翰大学在过去几年中发展的中子谱仪（参考文献9及处于准备阶段的稿件）对于识别这种冷核聚变过程是非常重要的。探测器包括一个放置在直径为12.5 cm的玻璃圆筒中的液体有机闪烁器（BC-505），该圆筒内嵌着三个掺杂有Li-6的玻璃闪烁器平板。中子通过多次碰撞将能量存积在液体闪烁器中，然后生成的光输出产生能量信息。由于能量减少了，中子就会被⁶Li核全部吸收，并且该反应 $n + {}^6\text{Li} \rightarrow t + {}^4\text{He}$ 会在玻璃中引起闪烁。来自两个闪烁器的脉冲波形和振幅不相同；这两个不同的信号会被两个光电倍增管记录下来，并把倍增管的信号相加。在20 μs内来自两个倍增管的可分辨的一致信号就能够识别出一个停在探测器内的入射中子。 英文

用d-d反应产生的，能量分别为2.9 MeV和5.2 MeV的中子来校准谱仪，这些中子相对于范德格拉夫加速器氘核束流的方向在90°和0°方向射出。观测到的能谱比较宽，这意味着2.45 MeV中子应该出现在多道分析器的第45到第150道之间。通过对铀-252广谱源裂变中子计数率的多次测量，检验了探测系统的稳定性。 英文

我们已做了大量的测试证实，在这种脉冲高度范围内，中子谱仪不会对像热中子这样的其他辐射源优先响应。特别是，我们企图通过使用多种 γ 射线、中子源和开/关辅助设备来产生 2.5 MeV 中子“信号”的努力都失败了。在所有的信号和本底运行中，我们关闭了像范德格拉夫加速器这样的中子产生装置。 [英文](#)

许多本底运行是用含标准电极和电解质的正在运行的电解池（下文将介绍）完成的，只是将其中的 D_2O 换成了 H_2O ；而其他的本底运行是用新的和之前用过的包含 D_2O 和平常电解质的无电流标准电解池完成。单个的本底运行是毫无特征的，且与图2所示的整体本底模式高度一致。在预期的 2.5 MeV 中子出现的能量范围内，中子计数器的本底率约为 10^{-3} s^{-1} 。通过对比 γ 射线和中子源的能谱，我们已经确定，在观测到的本底事件中，大约 $1/4$ 是由于 γ 射线的偶然重叠， $3/4$ 由周边环境中的中子引起。 γ 射线本底主要来源于周围材料中的放射性镭和钾。我们将环境中的中子归因于宇宙射线源。尽管典型的中子的发射谱（初生的）在接近 2.5 MeV 处有一个很宽的峰（参考文献10），但蒙特卡罗计算表明，由于源介质的小变化（主要是对探测器周围的屏蔽层引起）将消除这种结构，并产生一个在 0.5 MeV 以上的平滑递减的本底谱，这和观测结果一致。 [英文](#)

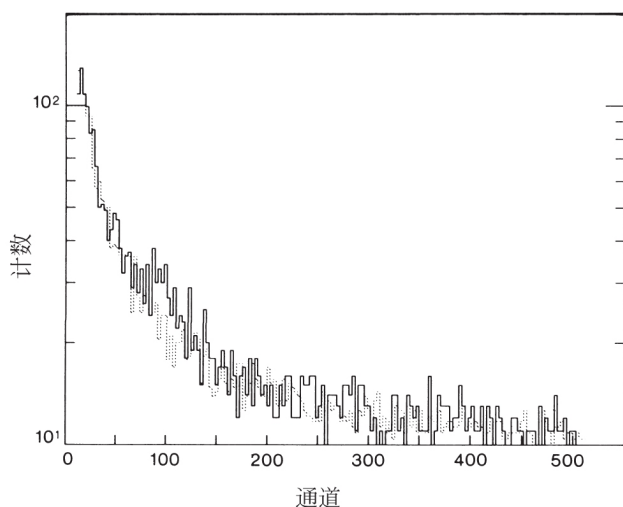


图2．信号（实线）和本底（虚线）计数关于中子谱仪中脉冲高度（对应于中子能量）的函数。为了表述清楚，我们在每3通道中加入10个计数。 [英文](#)

预期和测到的宇宙射线产生的中子谱中的这种结构的缺失，不会受

宇宙射线流中可能发生的相对微小而短暂的变化（如可观测到的与太阳耀斑相伴出现的减小）的影响。这就意味着，周边环境 neutron 本底的变化不能对 2.5 MeV 处所观测到的峰作出解释，因为，正像下文解释的那样，分析是基于谱的形状而不是简单地依据比率得出的。低能宇宙射线 μ 子应该被具有较高原子序数的原子核迅速清除掉，以便将 μ 子催化的 d-d 聚变降到可以忽略的水平上 [2,3]。考虑到体积和立体角，由检测器中碳核吸收的 μ 子产生中子的速率比在电解池中氧核吸收的 μ 子产生中子的速率要快近 60 倍。因此，电解池存在与否对本底的影响并不大。 [英文](#)

在寻找合适的催化剂材料的过程中，逐渐形成了下面对电解池的配方（非最优化的）。它从火山温泉中典型的盐类化合物开始，并要包含电极-金属离子。典型的电解质是一种混合物，包含约 160 g D_2O 与多种金属盐，每种金属盐的总量约为 0.1 g，其中包括： $FeSO_4 \cdot 7H_2O$ 、 $NiCl_2 \cdot 6H_2O$ 、 $PdCl_2$ 、 $CaCO_3$ 、 $Li_2SO_4 \cdot H_2O$ 、 $Na_2SO_4 \cdot 10H_2O$ 、 $CaH_4(PO_4)_2 \cdot H_2O$ 、 $TiOSO_4 \cdot H_2SO_4 \cdot 8H_2O$ 以及极少量的 $AuCN$ 。用 HNO_3 将 pH 值调整到 ≤ 3 。本文中所报道的这 14 次运行均从这一基础的电解质开始。 [英文](#)

最初选择钛和钯是由于它们能够大量储存氢并形成氢化物，结果发现它们还是有效的负电极。单个电极是由约 1 g 纯化的球形“熔融”钛组成，或者由 0.05 g 厚度为 0.025 mm 的钯箔组成，也可以由 5 g 表面粗糙的钯组成。通常会同时使用 4~8 个电解池。有时我们用稀释过的酸或磨蚀材料对钯箔的表面进行清洗、粗化，之后将其回收利用。仅仅在电解发生的几分钟之后，我们就观察到钯箔上形成了氢气泡，这说明氘核已经被迅速吸收进箔里；氧气泡也在阳极迅速形成。阳极材料为金箔。直流电源对每个电解池提供了 3~25 V 电压和 10~500 mA 电流。但是，聚变产额与电压、电流密度或金属阴极的表面特征间的关联还不确定。 [英文](#)

在每个高和直径均约为 4 cm 的小广口瓶中盛有约 20 ml 的电解质溶液。如图 1 所示，我们将电解池放在中子计数器的上面或旁边。无疑，目前的电解池非常简单，而且远远未达到最佳效果。但对于证实氘电注入金属期间的冷核聚变现象而言，这种带有中子谱仪的电解池组合已经足够了。 [英文](#)

图2给出了在上述条件下得到的能谱，且并列给出本底谱（已定标）。我们取得的本底数据大约是信号数据的两倍。保守地假设来自本底的所有偏差都是统计涨落，我们用大小为0.46的因子来定标本底计数，使它与图2所示的整个能量范围内的信号计数相匹配。在45~150道之间的一个特征峰高出本底将近4个标准偏差。这意味着，我们的假设太过保守，且这个结构显示了真实的物理效应。在以大小为0.44的因子对本底进行重新定标之后，我们得到了二者的差分图（图3），重新定标旨在使本底计数在稍低于和稍高于该特征峰的区域与信号水平相匹配。该图展示了一个集中于100道附近的强烈信号，其统计显著性几乎是5个标准偏差。高斯拟合后，有一个峰，其中心在101道附近，其标准偏差是28个通道，幅度为 23.2 ± 4.5 个计数。根据光谱仪校准，该特征峰的位置和宽度对应于2.5 MeV中子的期望值。在本底之上出现的显著信号对应的能量恰为d-d聚变的中子能量（约2.5 MeV），这一事实为电解质催化电解池中存在反应率很低的核聚变提供了强有力的证据。

英文

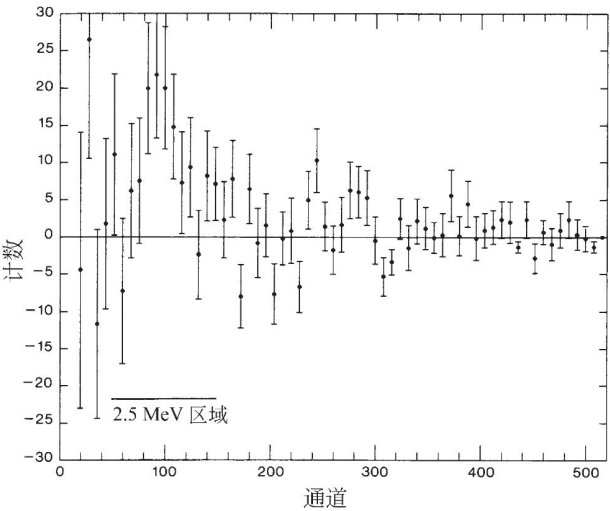


图3．通过从信号中减去定标的本底得到的差分谱图。图中给出每8个通道的统计误差（ $\pm 1\sigma$ ）。 英文

测定聚变率

对列入上文讨论的综合数据中的那14次运行分别进行考查是有益的。这些运行是在1988年12月31日至1989年3月6日期间完成的。图4给

出了每一次运行在2.5 MeV的能量区域内的信号计数率与本底计数率之比。在改变观察到的本底率的实验过程中，仪器中存在电子学的变化，所以我们根据信号/本底计数率的比值而非绝对计数率来绘制数据。在一组数据中（运行1到8），我们尽量使系统不受影响以避免本底率的改变，对2.5 MeV中子探测的测量率高出本底 $(6.2 \pm 1.3) \times 10^{-4} \text{ s}^{-1}$ 。在这组数据中，本底率和信号率对于所有约3 MeV以上（即190道到512道之间的所有道）的能量来说都是相等的，为 $(1.4 \pm 0.1) \times 10^{-3} \text{ s}^{-1}$ 。

英文

特别值得注意的是运行6，其在本底之上的统计显著性为将近5个标准偏差。我们将质量约为3 g的熔融钛小球作为负极。在电解开始一个多小时之后，中子产率增加了。约8个小时之后，中子产率却急剧地降低了，这点可以从后续的运行7看出。此时，在钛电极表面出现了一个深灰色的涂层。使用电子显微镜上的微探针进行分析后发现，该表面涂层主要是铁，而氦核在阴极沉积。同样的现象，即电解进行约8个小时之后中子信号减弱，也发生在运行13及其后的运行14中。运行13和运行14用的是相同的8个电解池，并且在电解开始的几个小时之后涂层又出现在了阴极上。这些观察结果揭示了表面状况对于冷核聚变过程的重要性。由于物质会从溶液中析出，所以每次测试运行中表面状况及电解质成分的变化是可以预料到的；并且溶液的pH值在一个运行过程中也会显著地变化。这14次运行展示了对于电极材料和多种工作电流的两个选择。这些变化或许可以解释图4中信号电平的明显波动。鉴于这些运行展示了总量只有约200个的信号中子，其平均产生率约为每小时2个，优化该实验条件是非常困难的。这是未来研究的一项任务。

英文

实验观察到的约8小时之后出现的信号“中断”或许可以解释运行1和3中的信号/本底的低比值，因为信号只能持续几个小时，在一个较长的运行时间（约20小时）之后，该信号可能早就被覆盖掉了。当运行10以明显高于本底的速率开始后，作为测试，我们停止该运行，并撤去一半的电解池。正如我们所料，中子产生率逐渐减少（运行11）。在检测数据的统计显著性时，我们将运行1、3、7、11和14包括进来，尽管我们看到了造成上文提到的它们较低的信号/本底之比的系统性原因。图4中所示的运行8从磁存储器中不幸丢失，因而在图2和图3中未显示出来，

但这并不影响我们的结论。 英文

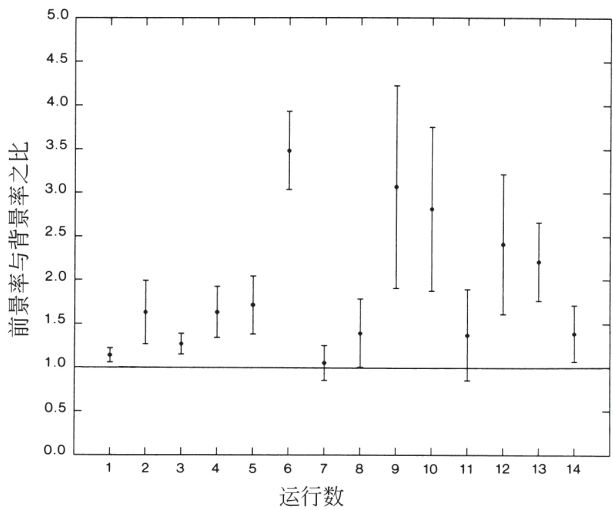


图4．在脉冲高度谱的2.5 MeV能区内，每个运行的信号率与本底率之比。图中给出统计误差（ $\pm 1\sigma$ ）。 英文

特别是对于运行6，我们可以用以下公式估计电解过程中d-d聚变产生中子分支的产率：

$$\text{每秒钟每个氘核对的聚变次数} = \frac{R / \varepsilon}{M \times \frac{d}{2M}} \tag{4}$$

其中，观测到的中子探测率 $R = (4.1 \pm 0.8) \times 10^{-3} \text{ s}^{-1}$ 是基于45~150道间的信号计数减去相应的本底计数得出的；用蒙特卡罗中子-光子传输编码^[11]计算出的中子探测效率（包括几何接受角）是 $\varepsilon = (1.0 \pm 0.3)\%$ ；而3 g 钛中含 $M \approx 4 \times 10^{22}$ 个钛原子；基于钛晶格中几乎所有的四面体位点均被占据的假设，氘核对与金属离子之比 $d/2M \approx 1$ ，形成 $\gamma\text{-TiD}_2$ 氢化物。利用方程（4），对产生中子分支的冷核聚变率的估算值 λ_f 为每秒钟每个氘核对内约 10^{-23} 次聚变。如果大多数聚变发生在表面附近，或者钛晶格远远没有被氘核占据，又或者利于聚变产生的条件间歇性出现，那么推断出的聚变率一定会大很多，大概是每秒钟每个氘核内对 10^{-20} 次聚变。 英文

我们注意到，这样的聚变率可以通过将分子中的氘核间距“挤压”至其正常值（ $0.74 \text{ \AA}$ ）的一半来得到。这样的聚变率如今可以在凝聚态物

质中观察到，表明可以用催化的“压核”聚变来解释^[1]。一个可能的原因是，在氘化金属晶格中形成了准电子，其有效质量是一个自由电子的几倍。众所周知，氢的同位素一般积聚在金属晶格的缺陷中^[12]，而局部的高浓度氢离子可能有利于压核聚变。因为在平衡氘化金属或混合物（比如甲胺-d₂氘化氯化物或铵-d₄氯化物）中，我们没有发现任何聚变发生的证据，所以我们推断非平衡条件是必需的。电解就是一种产生远离平衡态的条件的方法。 [英文](#)

通过改变诸如压强、温度和电磁场等外部参数，或许可以影响聚变的有效率，但是这种影响被看作是冷核聚变的另一种形式，即μ子催化聚变^[13]。 [英文](#)

结论

关于冷压核聚变^[1]的有关想法以及对存在于金属和地球地热区中的过量³He的观测，促使我们对电解池中的聚变进行了实验研究，该研究始于1986年5月。我们的电解质成分演变发端于地球化学的考虑，并且随着观测到结果而逐渐加以改变。虽然产生率波动很大，但聚变中子信号的出现一再被重现出来。既然我们的探索性研究已经揭露了一个小的压核聚变效应，接下来就要弄清影响聚变率的各种因素。 [英文](#)

我们的数据清楚地表明了需要远离平衡态条件的要求，并且该要求提示那些不同于电化学的方法也许同样可行。我们已经开始探索离子注入、增大压强和提高温度的作用，这些操作是为了模拟相应的地质条件。将凝聚态物质中的冷核聚变作为一种包括地质系统在内的金属氢系统的新型探测手段，以及作为一种单能中子源，或许是非常有用的。如果d-d聚变能够被催化，那么d-t聚变反应可能会更受青睐，因其核截面要大得多。尽管目前观测到的聚变率很低，但凝聚态物质中冷核聚变的发现至少为一条通往聚变能的新途径提供了可能性。 [英文](#)

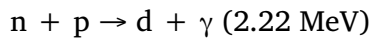
（牛慧冲 翻译；李兴中 审稿）

Problems with the γ -ray Spectrum in the Fleischmann *et al.* Experiments

R. D. Petrasso *et al.*

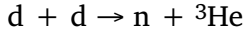
The claim by electrochemists Martin Fleischmann and Stanley Pons to have conducted “cold” nuclear fusion by electrolysis led to attempts worldwide to replicate the findings. Others focused on whether Fleischmann and Pons’ evidence supported their claims. A key argument was that they detected the neutrons and gamma-rays expected to be emitted, at well-defined energies, from the fusion reaction and its by-products. Here fusion expert Richard Petrasso of MIT and his colleagues investigate a gamma-ray spectrum shown on US television by Fleischmann and Pons (the only time they revealed it), and show that the alleged gamma-ray peak is in the wrong place. This challenge led to the first suspicions of fraud, rather than poor experimentation, in the cold-fusion claims. [中文](#)

SIR—Fleischmann, Pons and Hawkins¹ recently announced the observation of significant heating in their cold-fusion experiments, a result that they attribute to copious fusion reactions. As compelling evidence that fusion had occurred, they reported the observation of the 2.22-MeV γ -ray line that originates from neutron capture by hydrogen nuclei^{2,3}



(1)

(Here d represents a deuteron.) They contend that the neutron in reaction (1) is generated by the reaction



(2)

and conclude, therefore, first that the 2.22-MeV γ -ray confirms that the fusion process (2) is occurring, and second that a neutron production rate of the order of 4×10^4 neutrons s^{-1} is derivable from their γ -ray signal rate. They further state that most of the heat generation occurs not through process (2), but through a hitherto unknown nuclear-fusion process. [中文](#)

Here we focus solely on the identity of the reported γ -ray line, which we shall henceforth call the signal line. We argue that the claim of Fleischmann *et al.* to have observed the 2.22-MeV line characteristic of reaction (1) is unfounded. We do so on the basis of three quantitative considerations: (1) that the linewidth is a factor of two smaller than their instrumental resolution would allow; (2) that a clearly defined Compton edge⁴, which should be evident in their published data at 1.99 MeV, is not in fact present; and (3) that their estimated neutron production rate is too large by a factor of 50. In addition, from a consideration of the terrestrial γ -ray background, we argue that their purported γ -ray line actually resides at 2.5 MeV rather than 2.22 MeV. These conclusions are, in part, based on our studies of neutron capture by hydrogen, using a neutron source submerged in water. These measurements allow us to compare the results of Fleischmann *et al.* directly with a controlled experiment. [中文](#)

We measured terrestrial γ -ray background spectra in order to compare

our detector characteristics with those of Fleischmann *et al.* Figure 1a shows a typical terrestrial γ -ray background spectrum obtained with a 3 in. $\times$ 3 in. NaI(Tl) crystal spectrometer system (see ref. 5 for details). The main features of the background spectrum are quite similar throughout the terrestrial environment^{6,7}. Fleischmann *et al.* showed a similar γ -ray spectrum on television (Fig. 1b). (We believe that we have viewed all the cold-fusion γ -ray spectra that have been shown on KSL-TV (Utah) up to 19 April. This information was obtained from Utah News Clips, Inc., Utah. As far as we can tell, all spectra are identical to that of Fig. 1b.) This spectrum was obtained in the course of the Fleischmann *et al.* experiments (M. Hawkins, personal communication). Their spectrometer system consisted of a Nuclear Data ND-6 portable analyser with a 3 in. $\times$ 3 in. NaI (Tl) crystal (ref. 1 and M. Hawkins and R. Hoffmann, personal communications). A $\frac{3}{8}$ -in.-thick Pb annulus encompassed the scintillator. It is clear from Fig. 1a and b, and particularly from the ^{40}K (1.46 MeV) and ^{208}Tl (2.61 MeV) lines, that our resolution is comparable to or better than that of the spectrometer used by Fleischmann *et al.*, a point to which we return later. [中文](#)

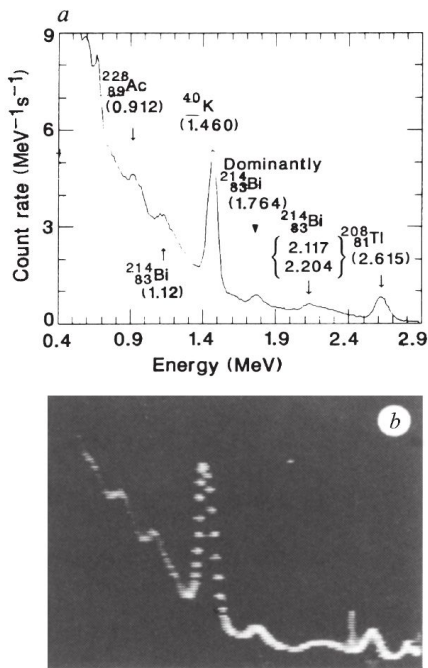


Fig. 1. *a*, The γ -ray background spectrum measured with a 3 in. $\times$ 3 in. NaI(Tl) detector at MIT. Some important terrestrial γ -ray lines have been identified in this figure^{6,7,12}. (As explained in ref. 12, the immediate parent of the final decay product is identified. For example, ^{40}K β^+ decays into an excited nuclear state of ^{40}Ar , which actually then emits the 1.460-MeV photon discussed in the text.) The spectrum is averaged over an 84-hour run. *b*, the γ -ray spectrum shown on television by Fleischmann *et al*. The main characteristics of the two spectra are similar; one can also tell that the two detectors have comparable spectral resolution. In *b*, note the curious structure at about 2.5 MeV and that beyond the ^{208}Tl peak (2.61 MeV), which appear to be artefacts. (The spectrum can also be obtained from KSL-TV in Utah (M. Hawkins, personal communication).) 中文

In the interval 1.46–2.61 MeV, the energy resolution of a NaI(Tl) spectrometer, which determines the γ -ray linewidth, can be well described by the formula^{8,9}

$$R(E) = \frac{\Delta E}{E} \approx R(E_n) \sqrt{E_n/E} \quad (3)$$

Here ΔE is the full width at half maximum (FWHM) of the line, E is the energy of the photon and $R(E_n)$ is the measured “reference” resolution at energy E_n . $R(E_n)$ can be accurately determined using a ^{60}Co source (that is, the ^{60}Co line at 1.33 MeV), or it can be fairly well approximated by the ^{40}K decay line at 1.46 MeV. (From Fig. 1*b*, the

⁴⁰K decay line allows one to estimate Fleischmann *et al.*'s resolution as ~8%.) Table 1 lists the resolution data for our detectors and for that of Fleischmann *et al.*. 中文

Table 1. Comparison of energy resolutions of the γ -ray spectrometers

(a) Resolution of MIT spectrometers					
Energy (MeV)	1.17 ⁶⁰ Co	1.33 ⁶⁰ Co	1.46 ⁴⁰ K	2.22 n(p, γ)d	2.61 ²⁰⁸ Tl
origin					
Natural background			0.055		0.043 (0.041)
⁶⁰ Co	0.056	0.051			
Pu/Be neutron source				0.05 (0.045)	
(b) Resolution of the Fleischmann <i>et al.</i> spectrometer ¹					
Energy (MeV)		1.33 ⁶⁰ Co	1.46 ⁴⁰ K	2.22 n(p, γ)d	2.61 ²⁰⁸ Tl
Reference					
Hoffman*		0.056	0.065		
TV news†			~0.08		~0.05 (0.049)
Ref. 1 (errata)				0.025 (0.053)	

The resolution is defined as the full width at half maximum (FWHM) divided by the peak energy. Numbers in parentheses are predicted values based on the detector resolution at 1.46 MeV (see text). In *b*, the prediction is based on the resolution value (0.065 at 1.46 MeV) provided by R. Hoffman (personal communication)

*R. Hoffman (personal communication).

† Derived from images of the televised news broadcasts. 中文

We now compare the signal line of Fleischmann *et al.* (Fig. 1a of ref. 1 (errata), shown as Fig. 2 here) with our measured spectrum obtained from the experiments on neutron capture by hydrogen (Fig. 3 here, and Fig. 4 of ref. 5). In these experiments, a Pu/Be neutron source was placed in a water tank. ²³⁹₉₄Pu emits energetic α -particles, which produce neutrons through (α , n) reactions with Be (refs 4,9). The neutrons are thermalized in water, and we observe the emitted neutron-capture γ -rays with our spectrometers. The measured resolution at 2.22 MeV is ~5% (Table 1a), and is reasonably well predicted by equation (3). As a consequence, this calls into immediate question the identity of Fleischmann *et al.*'s signal line as a γ -ray line. Specifically, Fig. 2 shows the signal line to have a resolution of 2.5%. This is about a factor of two smaller than that predicted by equation (3) on the basis of the known resolution (Table 1b) from either the ⁴⁰K

decay line (1.46 MeV) or from the ^{60}Co source (1.33 MeV) (R. Hoffman, personal communication). But we know from Table 1 that the spectrometer used by Fleischmann *et al.* has a resolution that is at best comparable to our own for the entire region from 1.46 to 2.61 MeV (see also Fig.1), so it is inconsistent that their linewidth at 2.22 MeV is a factor of two below the predicted value. 中文

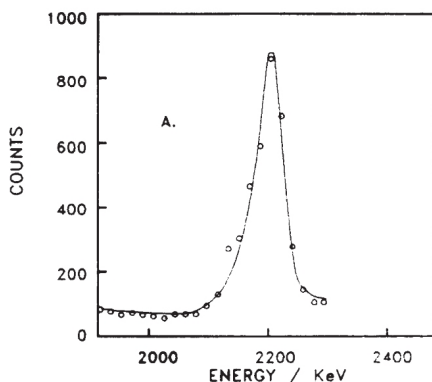


Fig. 2. A reproduction of the purported 2.22-MeV γ -ray signal line of Fleischmann *et al.* (Fig. 1a of errata to ref.1). The resolution, based on the linewidth, is about 2.5%. With such resolution, one would expect to see a clearly defined Compton edge at 1.99 MeV. No edge is evident. Also, a resolution of 2.5% is inconsistent with their spectral resolution. Furthermore, we argue that the signal line may reside at 2.5 MeV, not at 2.22 MeV as is claimed by Fleischmann *et al.* and depicted here. 中文

There is a second crucial inconsistency with the published signal line (Fig. 2). If we assume a resolution of 2.5% at 2.22 MeV, then there should be a clearly defined Compton edge⁴ at 1.99 MeV. For example, in Fig. 3 the Compton edge is evident even for our measured resolution of only 5%. For a resolution of 2.5%, the definition of the Compton edge would be distinctly sharper. The lack of a Compton edge at 1.99 MeV for the signal line therefore negates the conclusion of Fleischmann *et al.* that they have observed the 2.22-MeV γ -rays from neutron capture by hydrogen. 中文

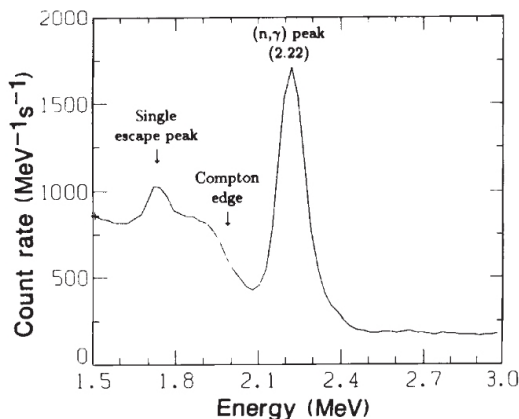


Fig. 3. The γ -ray spectrum measured by a 3 in. $\times$ 3 in. NaI(Tl) spectrometer during a neutron-capture-by-hydrogen experiment using a (Pu/Be) neutron source submerged in water. Because of the finite size of the crystal (which is identical to that of Fleischmann *et al.*¹), we also see an escape peak²⁻⁴ and, of particular importance here, the Compton edge⁴. In this figure, the digitization energy width is 0.024 MeV per channel. The full Pu/Be and background spectra are shown in Fig. 4 of ref. 5. [中文](#)

We also point out that in our (Pu/Be) neutron-capture experiments, a conspicuous e^+e^- annihilation single-escape peak exists at 1.71 MeV (Fig. 3), as well as a double-escape peak at 1.20 MeV. (The full spectrum from the Pu/Be experiment, as well as the background spectrum, can be found in ref. 5.) Such features unambiguously identify the primary γ -rays as having an energy of 2.22 MeV, and are a necessary consequence of the physical processes of detection of γ -rays in a finite-sized NaI scintillator. [中文](#)

Based independently on both their γ -ray and neutron measurements, Fleischmann *et al.* claim to have observed a neutron production rate of $\sim 4 \times 10^4$ neutrons s^{-1} (ref. 1). This claim is clearly inconsistent with their γ -ray signal line, for the following quantitative reasons. The Pu/Be neutron source used in our experiment is absolutely calibrated to within 10% of 1.5×10^6 neutrons s^{-1} (ref. 10 and MIT Reactor Radiation Protection Office). In obtaining the data in Fig. 3, we used an experimental setup similar to that of Fleischmann *et al.* (ref. 1; televised broadcasts; and M. Hawkins and R. Hoffman, personal communications). Our Pu/Be source was submerged 6 in. into a large

water tank. The rate at the 2.22-MeV peak, after subtracting the background continuum, is about $1.4 \times 10^3 \text{ MeV}^{-1} \text{ s}^{-1}$ (see Fig. 3). Scaling this rate to a neutron source of $4 \times 10^4 \text{ neutrons s}^{-1}$ (the level given by Fleischmann *et al.*), and integrating over the linewidth, gives a total 2.22-MeV γ -ray rate of about 4.5 counts per second. This value is a factor of 50 times higher than the rate that would be calculated on the basis of the results in Fig. 1a (that is, 0.081 counts per second). (Fleischmann *et al.* state that their neutron count rate is measured with a BF_3 neutron counter over a $0.4 \text{ mm} \times 10 \text{ cm}$ Pd cell, and that the γ -ray measurement is over a $0.8 \text{ mm} \times 10 \text{ cm}$ Pd cell¹. If the total reaction rate is proportional to the volume of Pd rod, as they state, the inconsistency in the reported neutron rate is by a factor of 200 rather than 50.) While differences in rates of a factor of two might possibly be explained by geometrical considerations, a factor of 50 is inexplicable. 中文

A further point concerning the identification of the signal line is the precise value of the energy at which the peak occurred. From Fig. 2, the background in the neighbourhood of the peak is seen to be ~ 80 counts per channel, a level that corresponds to ~ 400 counts per channel for a 48-hour accumulation time (the data in Fig. 2 were accumulated for a period of 10 hours¹). On the other hand, in the Utah measurements of terrestrial γ -ray background, the level in the vicinity of the 2.22-MeV feature was found to be $\sim 4,000$ counts per channel (R. Hoffman, personal communication). The only relevant part of the entire γ -ray spectrum (between 1.46 and 2.61 MeV) in which the background was as low as 400 counts was at an energy in the vicinity of 2.5 MeV (R. Hoffman, personal communication). Thus, we argue that the peak in the spectrum shown in Fig. 2 may be at 2.5 MeV, not at 2.22 MeV. 中文

The importance of properly identifying the energy of the feature claimed by Fleischmann *et al.* can hardly be overemphasized. Thus, it

is extremely unfortunate that they chose to display only the energy range 1.9–2.3 MeV in their published Fig. 1a, thereby not providing the supporting evidence of the ^{40}K (1.46-MeV) and ^{208}Tl (2.61-MeV) features which must be present in their spectra in order for their identification to be correct. 中文

Therefore, although Fleischmann *et al.* may have observed a change in their γ -ray spectra that bears some relation to detector location, we conclude that it is unrelated to the 2.22-MeV neutron-capture γ -rays, and that it is also unrelated to the background $^{214}_{83}\text{Bi}$ line (2.20 MeV; Fig. 1a), as has been suggested elsewhere¹¹. We can offer no plausible explanation for the feature other than it is possibly an instrumental artefact, with no relation to a γ -ray interaction. 中文

(339, 183-185; 1989)

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References:

1. Fleischmann, M., Pons, S. & Hawkins, M. *J. electroanalyt. Chem.* **261**, 301-308 (1989); and errata.
2. Hamermesh, B. & Culp, R. J. *Phys. Rev.* **92**, 211 (1953).
3. Greenwood, R. C. & Black, W. W. *Phys. Lett.* **6**, 702 (1966).
4. Knoll, G. F. *Radiation Detection and Measurements* (Wiley, New York, 1979).
5. Petrasso, R. D. *et al.* MIT Plasma Fusion Center Report PFC/JA-89-24 Rev. (1989).
6. Eisenbud, M. *Envir. Radioactivity* (Academic, New York, 1973).
7. Adams, J. A. S. & Lowder, W. M. *The Natural Radiation Environment* (Univ. of Chicago Press, 1964).
8. *Harshaw Radiation Detectors Scintillation Counting Principles*, Solon, Ohio, 44139 (1984).
9. Crouthamel, C. E. *Applied Gamma-Ray Spectrometry* 2nd edn (eds Adam, F. & Dams, R.) (Pergamon, Oxford, 1970).
10. Reilly, W. F. thesis, Massachusetts Institute of Technology (1959).
11. Koonin, S. E., Bailey, D. C. *Am. phys. Soc. Meet. Special Session on Cold Fusion*, Baltimore, Maryland, 1-2 May (1989).
12. Lederer, M. C., Hollander, J. M. & Perlman, I. *Table of Isotopes* 6th edn (Wiley, New York, 1967).

Acknowledgements. We thank V. Kurz, J. S. Machuzak, F. F. McWilliams and Dr S. C. Luckhardt. For the use of a spectrometer system, we thank Professor G. W. Clark. For discussions, we thank M. Hawkins and R. Hoffman of the University of Utah. For suggestions and criticisms, we are grateful to Dr G. R. Ricker Jr and Professor D. J. Sigmar. We are indebted to J. K. Anderson for assembling this document. For locating important references, we thank K. A. Powers. Supported in part by the US Department of Energy.

弗莱施曼等人实验中 γ 射线谱的问题

佩特拉索等

电化学家马丁·弗莱施曼和斯坦利·庞斯宣称通过电解实现了“冷”核聚变，这引发了世界范围内去重复这一发现的尝试。而另一些人则关注弗莱施曼和庞斯的证据是否能够支持他们的结论。争论的关键在于他们是否在聚变反应和它的副产物中观测到了预期中的具有特定能量的中子和 γ 射线发射。麻省理工学院的核聚变专家理查德·佩特拉索和他的合作者研究了弗莱施曼和庞斯在美国的电视节目上演示的 γ 射线谱（这是他们唯一一次展示该图谱），并指出他们所声称的 γ 射线峰处于错误的位置。这一质疑引发了人们对冷核聚变的报告中存在欺诈的首次怀疑，而不仅仅只是对简陋实验的质疑。

英文

弗莱施曼、庞斯和霍金斯^[1]最近宣称在他们的冷核聚变实验中观察到了明显的放热现象，他们将这一结果归因于大量的聚变反应。作为核聚变发生的强有力的证据，他们在报道中说发现了2.22 MeV的 γ 射线，该射线源于氢原子核对中子的捕获^[2,3]

$$n + p \rightarrow d + \gamma(2.22 \text{ MeV})$$

(1)

（其中d代表一个氘核。）他们认为反应（1）中的中子产生于下述反应

$$d + d \rightarrow n + {}^3\text{He}$$

(2)

由此得出如下结论：首先，2.22 MeV的 γ 射线证实了核聚变过程（2）的

发生；其次，量级为每秒 4×10^4 个中子的中子产生速率可以由他们的 γ 射线信号的产生速率推导而来；他们进一步声明大多数热量的产生并非通过过程（2），而是通过一个迄今为止并不清楚的核聚变过程。

英文

我们在本文中主要关注如何识别报道的那条 γ 射线，本文中我们将称之为信号线。我们认为弗莱施曼等人所声称的反应（1）中观察到的2.22 MeV的特征谱线其实并未被找到。我们这么认为主要基于以下三个定量的考虑：（1）谱线宽度是他们的仪器所允许的分辨率的一半；（2）在他们发表的数据中本应位于1.99 MeV的清晰可辨的康普顿边^[4]，却没有出现；（3）他们估算的中子产率大了50倍。更进一步地说，考虑到地面的 γ 射线本底，我们怀疑他们所声称的 γ 射线实际上位于2.5 MeV处，而非2.22 MeV处。这些结论部分基于我们对氢捕获中子的研究，该研究通过将中子源浸没在水中进行。这些测量使得我们可以将弗莱施曼等人的结果与对照实验进行直接对比。

英文

为了比较我们与弗莱施曼等人的探测器的特性，我们测量了地面的本底 γ 射线谱。图1a显示了一个典型的地面本底 γ 射线谱，该光谱由3 in $\times$ 3 in碘化钠（铯）晶体光谱仪系统（详见参考文献5）测得。在整个地面环境中 γ 射线本底谱的主要特征都非常相似^[6,7]。弗莱施曼等人在电视上展示了一个类似的 γ 射线谱（图1b）。（我们相信我们看到了截止到4月19日在KSL电视台（犹他州）播出的所有的冷核聚变的 γ 射线谱。此信息从犹他州的犹他新闻剪影公司获得。在我们所能分辨的范围内，所有的光谱都与图1b所示的相同。）这个 γ 谱是从弗莱施曼等人的实验中获得（霍金斯，个人交流）。他们的光谱仪系统由一个装有3 in $\times$ 3 in碘化钠（铯）晶体的ND-6型便携式核数据分析仪组成（参考文献1以及与霍金斯和霍夫曼的个人交流）。一个3/8 in厚的铅圆筒包裹着闪烁体。从图1a和1b中，尤其是 ^{40}K （1.46 MeV）和 ^{208}Tl （2.61 MeV）的谱线中看得非常清楚，我们的分辨率与之相当或者优于弗莱施曼等人的 γ 谱仪，这一点我们后面还会谈到。

英文

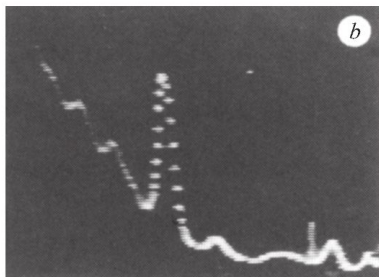
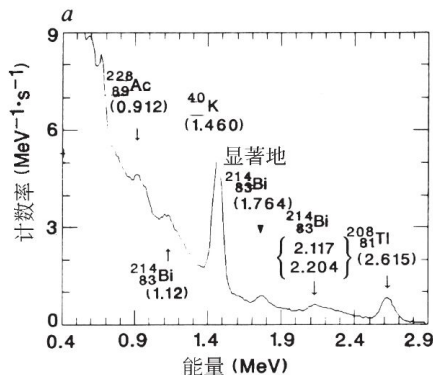


图1 . *a* , 用一个3in×3in碘化钠（铊）探测器在麻省理工学院测得的 γ 射线本底谱。一些重要的地面 γ 射线谱线在图中被标示出来[6,7,12]。（正如参考文献12中所解释的那样，最终衰变产物的瞬态母核是可以辨认的。例如， ^{40}K 经 β^- 衰变后转变为处于核激发态的 ^{40}Ar ，其实这个核然后会放射出文章中讨论的1.460 MeV的光子。） γ 谱是经过84小时测量后所取的平均值。*b* , 弗莱施曼等人在电视上展示的 γ 射线谱。两张 γ 谱的主要特征是相似的；两个探测器具有相当的 γ 谱分辨率。*b*中，注意在大约2.5 MeV处和超出 ^{208}Tl 峰（2.61 MeV）处的奇异结构，看上去像是伪造的。（ γ 谱也可从犹他州的KSL电视台获得（霍金斯，个人交流）。） [英文](#)

在1.46~2.61 MeV区间内，决定 γ 射线线宽的碘化钠（铊） γ 谱仪能量分辨率可以由下式描述[8,9]

$$R(E) = \frac{\Delta E}{E} \approx R(E_n) \sqrt{E_n/E} \quad (3)$$

其中 ΔE 是 γ 谱线的半高宽（FWHM）， E 是光子的能量， $R(E_n)$ 为能量 E_n 处测量的“参考”分辨率。 $R(E_n)$ 可以使用 ^{60}Co 源（即在1.33 MeV处 ^{60}Co 的谱线）进行准确的测定，或者通过 ^{40}K 在1.46 MeV处的衰变谱线进行相对准确的估算。（通过图1*b*中 ^{40}K 的衰变谱线可以估算出弗莱施曼等人的 γ 谱仪分辨率约为8%。）表1列出了我们和弗莱施曼等人的探测器的分辨率数据。 [英文](#)

表1. 两组 γ 射线谱仪能量分辨率的对比

(a) 麻省理工学院 γ 谱仪的分辨率					
能量(MeV)	1.17 ⁶⁰ Co	1.33 ⁶⁰ Co	1.46 ⁴⁰ K	2.22 n(p, γ)d	2.61 ²⁰⁸ Tl
源					
自然本底			0.055		0.043 (0.041)
⁶⁰ Co	0.056	0.051			
钚/铍中子源				0.05 (0.045)	
(b) 弗莱施曼等人的 γ 谱仪的分辨率 ^[1]					
能量(MeV)		1.33 ⁶⁰ Co	1.46 ⁴⁰ K	2.22 n(p, γ)d	2.61 ²⁰⁸ Tl
参考					
霍夫曼*		0.056	0.065		
电视新闻†			~0.08		~0.05 (0.049)
参考文献 1 (勘误)				0.025 (0.053)	

本分辨率定义为半高宽（FWHM）除以峰值的能量。括号中的数字为基于探测器在1.46 MeV处的分辨率预测的数值（见文中）。在b中，预测值是基于霍夫曼（个人交流）提供的分辨率数值（1.46 MeV处为0.065）得出的。

* 霍夫曼（个人交流）。

† 从电视新闻节目的图像获得。 [英文](#)

我们现在将弗莱施曼等人的信号线（参考文献1（勘误）中的图1a，即本文所示的图2）与我们在氢捕获中子的实验中测量的 γ 谱（本文的图3和参考文献5的图4）来进行对比。在这些实验中，一个钚/铍的中子源被放置在水槽中。²³⁹94Pu放射出具有一定能量的 α 粒子， α 粒子与铍通过（ α ，n）反应产生中子（参考文献4、9）。中子在水中达到热平衡，我们通过我们的 γ 谱仪对产生的中子捕获 γ 射线进行观测。测量的分辨率在2.22 MeV处约为5%（表1a），这一分辨率可以通过方程（3）合理地预测出来。因而，这立即引出了弗莱施曼等人的信号线作为 γ 射线峰的验证问题。具体来说，图2表明信号线具有2.5%的分辨率。这是从⁴⁰K的衰变谱峰（1.46 MeV）或者⁶⁰Co源（1.33 MeV）获知的分辨率（表1b）的基础上根据方程（3）计算出的分辨率的二分之一（霍夫曼，个人交流）。但是我们从表1知道，弗莱施曼等人使用的 γ 谱仪分辨率在1.46 MeV到2.61 MeV的整个范围内至多与我们的仪器相当（见图1），而这与他们在2.22 MeV处的线宽只有推算值的二分之一不相符。

[英文](#)

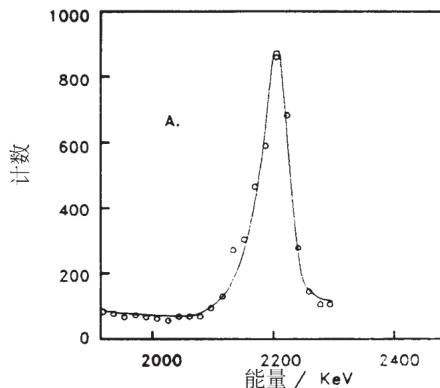


图2．弗莱施曼等人所声称的2.22 MeV的 γ 射线信号线的重复实验（参考文献1的勘误中的图1a）。基于线宽，分辨率约为2.5%。在这样的分辨率下，预期可以在1.99 MeV处看到清晰可辨的康普顿边。可是显然没有康普顿边。另外，2.5%的分辨率与他们的 γ 谱分辨率不符。进一步说，我们怀疑那个信号线可能位于2.5 MeV处，而不是弗莱施曼等人所声称的以及这里所展示的2.22 MeV处。 [英文](#)

发表出来的信号线（图2）还有第二个严重的矛盾。如果我们假设2.22 MeV处的分辨率为2.5%，那么在1.99 MeV处应该有一个清晰可辨的康普顿边^[4]。比如，即使对于我们的测量分辨率仅有5%的结果而言，图3中的康普顿边也非常明显。对于2.5%的分辨率而言，康普顿边的轮廓应该更锐利。信号线在1.99 MeV处康普顿边的缺失否定了弗莱施曼等人观察到的氢捕获中子产生2.22 MeV的 γ 射线的结论。 [英文](#)

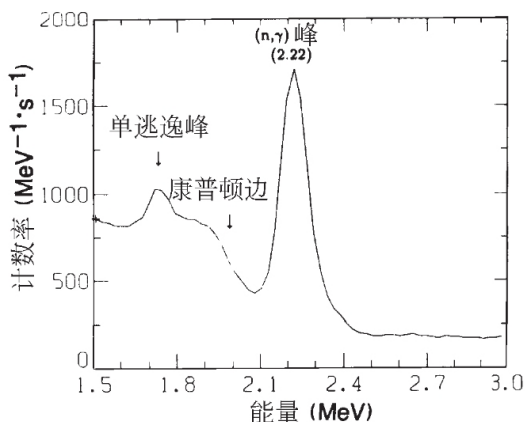


图3．在使用浸入水中的（钚/铍）中子源进行的氢捕获中子的实验中，通过一个3in×3in碘化钠（铯） γ 谱仪测得的 γ 射线谱。因为晶体的有限尺寸（与弗莱施曼等人^[1]使用的完全相同），我们也看到了逃逸峰^[2-4]，尤其重要的是，我们看到了康普顿边^[4]。本图中，数字化能量的宽度为每通道0.024 MeV。钚/铍以及本底的全谱示于参考文献5中的图4。 [英文](#)

我们也要指出，在我们的（钷/铍）中子捕获实验中，一个明显的正负电子湮灭的单逃逸峰出现在1.71 MeV处（图3），在1.20 MeV处也存在一个双逃逸峰。（钷/铍实验中的全谱以及本底光谱都可以在参考文献5中找到。）这些特征毫无疑问地确认了初始的 γ 射线具有2.22 MeV的能量，这也是用一个有限尺寸的碘化钠闪烁体探测 γ 射线的物理过程的必然结果。 [英文](#)

分别基于他们的 γ 射线和中子测量的结果，弗莱施曼等人声称观察到了约为每秒 4×10^4 个中子的中子产生速率（参考文献1）。基于下述的几个定量分析，这一结论与他们的 γ 射线信号线明显不符。我们实验中使用的钷/铍中子源经过了校准，中子产率为每秒 1.5×10^6 个中子，该值的校准精度为10%（参考文献10和麻省理工学院反应堆辐射防护办公室）。在获得图3的数据的过程中，我们使用的实验装置与弗莱施曼等人所使用的装置类似（参考文献1；电视广播；与霍金斯和霍夫曼的个人交流）。我们的钷/铍中子源被浸入水槽中的水下6 in处。对应于2.22 MeV的峰的中子产生速率在扣除连续的本底之后大约为每MeV每秒 1.4×10^3 个中子（见图3）。将这个速率放大到每秒 4×10^4 个中子（弗莱施曼等人所给出的水平），对整个线宽进行积分，得出整个2.22 MeV的 γ 射线的产生速率为每秒4.5个中子。这一数值是根据图1a中的结果计算出来的速率（即每秒0.081个中子）的50倍。（弗莱施曼等人指出，他们的中子计数速率是用一个三氟化硼中子计数器在一个0.4 mm $\times$ 10 cm的钷电解池上测得的，而 γ 射线的测量是在一个0.8 mm $\times$ 10 cm的钷电解池上进行的^[1]。如果整个反应的速率如他们所说的正比于钷棒的体积，那么报道的中子产生速率的差别将达到200倍而不是50倍。）反应速率存在两倍的差异也许可以从几何尺寸方面给予解释，但相差50倍的原因就无法解释了。 [英文](#)

关于信号线的确认更进一步的问题是谱峰出现位置的能量的准确值。从图2中，临近谱峰的本底看上去约为80计数/通道，这个量级与累计48小时约400计数/通道的值是相对应的（图2中的数据累积了10小时^[1]）。另一方面，在犹他州测量的地面 γ 射线本底中，在2.22 MeV特征峰附近的本底数量级约为4,000计数/通道（霍夫曼，个人交流）。而整个 γ 射线谱（1.46~2.61 MeV）的本底都低至400计数，其中唯一与之相

当的部分就是在能量2.5 MeV附近（霍夫曼，个人交流）。因此，我们质疑图2中 γ 谱的谱峰可能位于2.5 MeV处而不是在2.22 MeV处。

英文

对弗莱施曼等人声称的特征峰进行正确分辨的重要性再怎么强调都不为过。然而，非常遗憾的是在他们发表的图1a中仅展示了1.9~2.3 MeV的能量范围，却没有提供 ^{40}K （1.46 MeV）和 ^{208}Tl （2.61 MeV）的特征峰作为支持的证据，而为了证实他们的观点是正确的，这些峰本应出现在他们的谱图中。

英文

因此，尽管弗莱施曼等人可能在他们的 γ 射线光谱中观察到了某种由探测器位置改变所造成的变化，但正如之前人们所提出的那样^[11]，我们认为那与2.22 MeV的中子捕获 γ 射线并无关联，也与本底的 $^{214}_{83}\text{Bi}$ 谱线（2.20 MeV；图1a）无关。除了认为可能是仪器出错，而与 γ 射线的作用无关以外，我们不能够为这个现象提供其他可信的解释。

英文

（李琦 翻译；李兴中 审稿）

Upper Bounds on “Cold Fusion” in Electrolytic Cells

D. E. Williams *et al.*

When electrochemists Martin Fleischmann and Stanley Pons claimed to have found evidence of “cold” nuclear fusion happening in a small flask of salty heavy water undergoing electrolysis, conflicting reports of verification or failure quickly came from all over the world. This paper by chemist David Williams and his co-workers in England was one of the first to turn the tide of opinion towards the idea that cold fusion is an illusion. It reports a very comprehensive attempt to replicate the results of Fleischmann and Pons, and finds no evidence of excess heat, neutron emission or the formation of tritium—the last two being diagnostic of deuterium fusion. [中文](#)

Experiments using three different calorimeter designs and high-efficiency neutron and γ -ray detection on a wide range of materials fail to sustain the recent claims of cold fusion made by Fleischmann *et al.*¹ and Jones *et al.*². Spurious effects which, undetected, could have led to claims of cold fusion, include noise from neutron counters, cosmic-ray background variations, calibration errors in simple calorimeters and variable electrolytic enrichment of tritium.

[中文](#)

RECENT publications^{1,2} reporting electrochemically induced nuclear fusion, at room temperature, have aroused great interest. The signatures reported are excess heat output, neutron emission and tritium generation from cells with palladium cathodes¹, and neutron emission alone at a much lower level from cells with titanium cathodes². Conventional nuclear physics predicts that fusion between light nuclei requires either very high temperature (as in a tokamak) or unusually close proximity of the two nuclei (as in muon-catalysed fusion). The calculated fusion rate at the internuclear separation in the deuterium molecule (0.74 Å) is $\sim 3 \times 10^{-64} \text{ s}^{-1}$ (ref. 3), so the rates reported in ref. 2 ($\sim 10^{-23} \text{ d-d-pair}^{-1} \text{ s}^{-1}$; d is deuteron) are not easy to understand in the context of the known interstitial-site separations ($\sim 3 \text{ Å}$), even more so when it is realized that this rate is a severe underestimate because of incomplete deuterium loading in titanium (see Materials characterization section). The reaction rates reported in ref. 1 are even more difficult to understand⁴, and the existence, despite strong arguments to the contrary (ref. 5, for example), of an unknown mechanism, which results both in an extraordinary enhancement of the reaction rate and a suppression of the normal nuclear-reaction channels, has been postulated. 中文

In the first reports of the electrolytic cold fusion effect it was stated that the effect is not consistently reproducible, and that it both takes some time to appear and that it may subsequently disappear. Because electrochemical phenomena can be sensitively affected by the state of the surface, some irreproducibility is not, in itself, surprising, and other recent reports (refs 6–8, for example) give well documented accounts of failures as well as successes (R. A. Huggins and A. J. Appleby, Workshop on Cold Fusion, Santa Fe, May 1989) in observing the claimed effects. The clear lack of reproducibility necessitates significant replication, with controls at least equal in number to the number of tests, if positive results are to be viewed with confidence, and exploration of many different, well characterized, material and

electrolyte combinations. Particularly, the timescales and achievable concentrations for electrolytic loading of deuterium into palladium and titanium, the quantities of hydrogen “impurity”, and the species detectable by surface analysis of used cathodes ought to be determined. [中文](#)

Calorimetry

We used three types of calorimeter. First, we built calorimeters of size and design similar to those used by Fleischmann *et al.* (ref. 1 and M. Fleischmann, personal communication) (Fig. 1). We found these to be inaccurate instruments with some very subtle sources of error which it is necessary to appreciate and analyse in detail. We used sixteen such cells, containing different-size cathodes (1-, 2-, 4- or 6-mm Pd rods) and different electrolytes (0.1 M LiOD, 0.1 M LiOH, 0.1 M NaOD or 0.1 M NaOH). Figure 2*a, b* shows the results obtained for a typical cell. An immediately evident characteristic is the sloping baseline, with the sawtooth pattern a consequence of the regular refilling of the cell. The baseline slope can be quantitatively accounted for by a variation of the calibration constant, k , with the level of liquid in the cell. This is a result of radiative losses through the vacuum jacket⁹ and conduction of the glass inner wall of the cell¹⁰ (see Fig. 2 legend). A consequence of the sloping baseline is that any calibration is only valid for a particular liquid level. We regularly refilled these cells to a reference level at which the calibration had been performed. We calibrated the cells with the heaters before the electrolysis was started and again much later in the run, during the electrolysis, as is evident in Fig. 2*a* (see Fig. 1 legend for details of the calibration procedure). There was no statistically significant difference between the different calibration sets, so all data were combined. [中文](#)

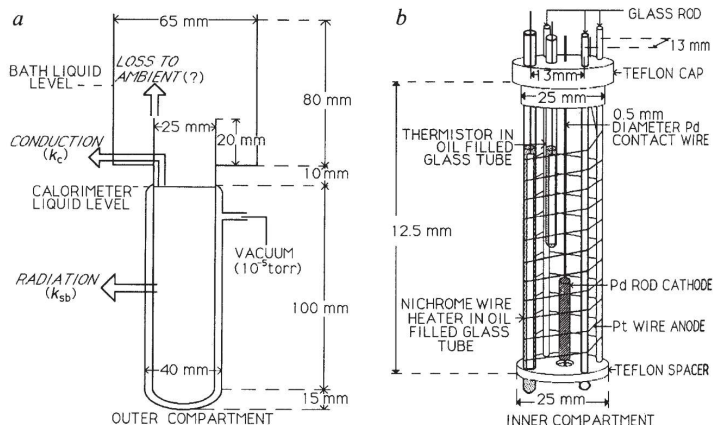


Fig. 1. Schematic diagram of the FPH-type heat-flow calorimeter used here. Heat flow paths are indicated here and discussed further in Fig. 2 legend.

METHODS. As well as the Fleischmann, Pons and Hawkins (FPH) type, we used¹⁰ two other calorimeter types—an improved heat-flow calorimeter (IHF) and an isothermal calorimeter. The IHF calorimeters differed from the FPH type in three important ways. First, they were larger: a 500-ml-capacity cylindrical vessel constituted the cell, with anode-cathode spacing ~ 2 cm. Second, the electrolysis vessel was inserted, using a film of oil for thermal contact, into a tightly fitting aluminium can which was itself packed around with insulating material and placed in a Dewar flask. Whereas the temperature of the cell contents in the FPH calorimeter was determined using a glass-clad thermistor immersed in the cell itself, in the IHF design the temperature of the aluminium can was measured: the can defined an isothermal surface for conduction of heat away from the cell and its use as the temperature measurement surface eliminated the sloping-baseline problem of the FPH design. Third, the space within the Dewar flask above the electrolysis vessel was filled with a polystyrene cap extending well above the Dewar flask, with the aim of significantly reducing unquantified heat losses to the atmosphere. The two types of heat-flow calorimeter were operated in water baths held at a constant temperature of $20^\circ\text{C}(\pm 0.08^\circ\text{C})$. The tops of the water baths were covered with a polystyrene lid. In both cases the cells comprised a spirally wound Pt wire anode (0.25 mm) and a central Pd cathode (Johnson Matthey). For the FPH cells we prepared the different electrolytes using either conductivity water (H_2O cells) or slightly tritiated D_2O (specific activity 13 kBq ml^{-1}) of isotopic purity initially $>99.9\%$. We used 0.1M LiOD (D_2O from Aldrich, measured $>99.9\%$ initial isotopic purity) as the electrolyte in the IHF calorimeters. The Pt and Pd contact wire was shrouded in glass tubing in the IHF cells to prevent any possible catalytic recombination of the electrolysis products. In later experiments with the FPH cells we also used screened electrode contacts, but this had no effect on the results obtained. The IHF cells contained a Pd wire electrode insulated to the very tip, which was positioned about three-quarters of the way up the cell. This was used to define the internal liquid level during filling, or refilling, of the cell. The larger volume of electrolyte in the IHF cells (300 ml) meant that refilling was required only occasionally, but the large thermal mass meant that the response was slow (time constant ~ 12 h); thus they were not

sensitive to small bursts of heat. We calibrated the heat-flow calorimeters using a nichrome wire heater placed in an oil-filled glass tube which was in contact with the cell contents. The calibration procedure involved operating the heater, either without electrolytic current, or with a current significantly less (0.2–0.4 times) than the normal electrolysis current, until a steady-state temperature was attained. With the FPH cells, use of a lower electrolysis current ensured continued stirring while diminishing the errors arising from the baseline drift; before each individual calibration the cells were refilled. An empirical calibration curve was thus obtained by fitting the observed thermistor resistance, R , to a range of applied powers, P , using the equation $P = a - b(\log R) + c(\log R)^2$, where a , b and c are the fitted parameters. The standard error of estimate on the fitted curve varied from 10 to as much as 70 mW with the FPH cells, largely reflecting the error in extrapolation to the reference level. Neutron counting was performed in conjunction with the operation of the FPH cells, using two independent banks of counters mounted above the cells, on top of the water-bath cover¹⁰. Detection sensitivity above background was 3 event s⁻¹ in the cell. We never observed a signal above background. The isothermal calorimeter (J. A. Mason, R. W. Wilde, J. C. Vickery, B. W. Hooton and G. M. Wells, Proc. 29th A. Meet. Inst. Nuclear Materials Management, Las Vegas, Nevada, June 1988) comprises three concentric aluminium cylinders each separated by a heat transfer medium with a relatively low thermal conductivity. The cylinder temperatures are maintained by electrical heaters wound as helical coils around each cylinder. Temperature control is achieved by resistance thermometers on each cylinder which are used in conjunction with classical control software and the cylinder heaters. The rate of thermal energy evolution in the measurement chamber (12.5-cm diameter, 26-cm high) is determined by measuring precisely the electrical power supplied to the chamber. We operated the calorimeter at a measurement-chamber temperature of $42 \pm 0.001^\circ\text{C}$. The measurement-chamber power resolution is <5 mW for an operating power of 20 W. The electrolytic cell contained ~ 1 L 0.1M LiOD. The cathode was contained in a perforated glass canopy to prevent the evolved gases from mixing inside the measurement chamber. The anode was a Pt foil cylinder 3 cm high and 12 cm in diameter surrounding the cathode. The cell was thermally coupled to the calorimeter measurement chamber by conducting oil. Measurements using Pt cathodes and also using nichrome wire heaters showed that there was a small systematic error in the calorimeter, an apparent power excess that varied linearly with the input power up to 100 mW for an input of 15 W. A linear fit to these measurements (12 points, standard error of estimate 8.8 mW) was therefore used to apply a correction to the apparent excess measured for the Pd cathodes. The measured output power of both the isothermal and IHF cells was corrected for the power loss that is due to evaporation of the electrolyte, assuming that the electrolysis gases were saturated in water vapour as they passed out of the cell (25.0 mW A⁻¹ at 42°C): $q_v = (p_v/p_0)(1.5)\Delta H_v/(2F)$ where q_v is the power loss, p_v denotes the saturation vapour pressure and ΔH_v the latent heat of evaporation of the electrolyte, p_0 is the atmospheric pressure, F is the Faraday constant and I is the current (assumes ideal gases).

[中文](#)

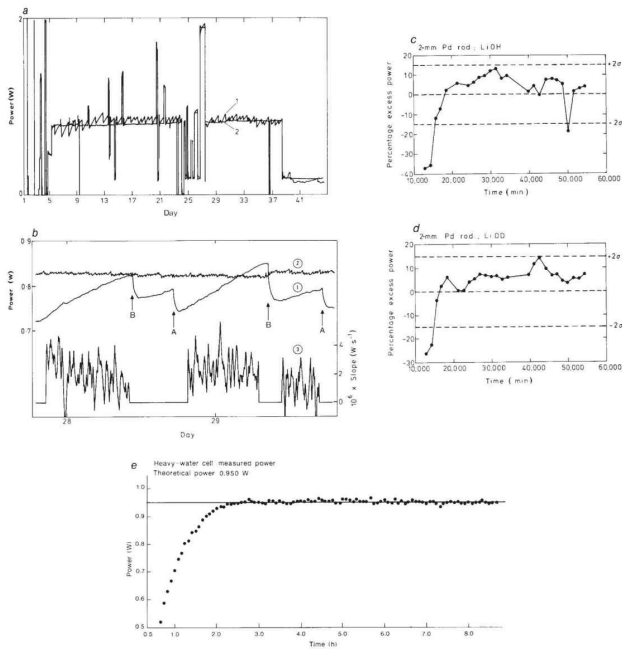


Fig. 2. *a*, Raw data from FPH-type calorimeter containing a 4-mm Pd rod (1.5 cm long, Johnson Matthey “specpure”, drawn from sintered stock) in LiOH electrolyte. Line 1 represents the output power calculated from the thermistor reading and line 2 represents the Joule input power to the cell, $P_{in} = I(V - V_0)$ where $V_0 = \Delta H_d / 2F$ (1.527 V for D_2O and 1.481 V for H_2O , ΔH_d being the enthalpy of dissociation, for example, $D_2O(l) \rightarrow D_2(g) + 1/2 O_2(g)$). The large step variations are calibrations. *b*, An expanded region of *a*, which emphasizes the sloping baseline. Lines 1 and 2 are as in *a*. Line 3 is the gradient of the apparent output power calculated by differentiation of the data using a seven-point Savitzky–Golay routine²³, stepping one point at a time. At points A the calorimeter was topped up to the reference mark with H_2O pre-warmed to the cell temperature. At points B a volume of liquid estimated from the electrolysis rate was added. *c* and *d*. Results for the *c* and *d*, Results for the two most consistently exothermic FPH calorimeters—0.2 × 3-cm Pd rod in (1) LiOD and (2) LiOH—in the form of percentage excess of apparent output power over the Joule input power. The error bars represent the control limits $\pm 2\sigma$ calculated from the results obtained for all the different cells (see text). *e*, Raw data obtained using the isothermal calorimeter (20 × 2-mm diameter Pd cathode), immediately following the application of the input power, with the line representing the Joule input power and the dots the observed cell power. The response time of this calorimeter is governed by the time to obtain thermal mixing of the cell contents, and is faster than that of the simple calorimeters, despite the large solution volume.

Sloping baseline. The response of the “simple” FPH calorimeter can be modelled by¹⁰

$$P_{in} = k\Delta T = (k_{sb} + k_c)\Delta T$$

(3)

where⁹,

$$k_{\text{sb}} = \sigma A_1 [T_1^4 - T_0^4] / \Delta T \approx 4\sigma A_1 T_0^3 [1 + 3\Delta T / (2T_0)] = k_{\text{sb},0} (1 + 3\Delta T / (2T_0)) \quad (4)$$

and¹⁰

$$k_{\text{c}} \approx \kappa A_2 / l = \kappa A_2 / (l_0 + IV_{\text{m}} \delta t / (2F\pi r_i^2)) \approx k_{\text{c},0} (1 - \alpha \delta t)$$

(P_{in} is the Joule input power, k is the calorimeter constant, k_{sb} and k_{c} are the contributions to the calorimeter constant of radiative losses through the vacuum jacket and conduction up the glass inner wall respectively, σ is the Stefan–Boltzmann constant, A_1 is the contact area of the solution with the wall of the cell, T_0 is the bath temperature, T_1 is the cell temperature, $\Delta T = T_1 - T_0$, κ is the thermal conductivity of the glass, l is the distance from the liquid to the point where the inner glass wall comes into contact with the bath and its initial value is l_0 , A_2 is the cross-sectional area of the inner glass wall, I is the cell current (300 mA), V_{m} is the molar volume of cell solution, δt is the elapsed time after refilling the cell, r_i is the internal radius of the glass vessel and $\alpha = IV_{\text{m}} / (2F\pi r_i^2 l_0)$). We measured the calorimeter constant for the cells to be $\sim 0.1 \text{ W K}^{-1}$, with the calculation using equation (4) indicating roughly equal contributions from k_{sb} and k_{c} . A more complete description of the calorimeter should also take into account the effects of the solution loss on the heat capacity of the calorimeter. It can be shown however that the contribution of this to the sloping baseline is insignificant¹⁰. 中文

Fig. 2c shows results for two of the calorimeters at the calibrated liquid level, in the form of percentage excess of apparent output power over the Joule input power. There was apparently an endothermic period at the beginning of the run, whose duration increased with cathode diameter. We speculate that this was due in part to poor stirring of the solution during hydrogen uptake by the cathode which caused a temperature gradient in the cell (gas is not at first evolved at the cathode and the larger diameter cathodes were shorter, to keep a constant surface area). An analogous effect at the start of the electrolysis was reported by Lewis *et al.*⁸, who showed that the apparent heating coefficient of a similar cell varied during the first part of a run. Because of this effect, we excluded the first 10,000 minutes of data from each cell when calculating the statistics. Table 1a shows the mean absolute power deviation for each cell and the standard deviation in this value. The standard deviation for all of the H₂O cells was not significantly different from that of the D₂O cells (F test, 1% level) so that the data from all of the cells can be used to

estimate the error: $\sigma = 0.048 \text{ W}$ (that is $\pm 5\text{--}10\%$). A more detailed analysis of this error¹⁰ showed it to be largely determined by the variability in the liquid level after refilling the cell, but also with a contribution from unquantified variations in the heat loss by conduction up the calorimeter wall to the air above the water bath. Compared with these errors, effects that resulted from temperature gradients inside the cells were minor. The design used here varied from that in ref. 1 in that the glass sleeve that supported the calorimeter and which was in direct contact with the inner wall, provided a large area of thermal contact with the water bath, and thus reduced the effect of the ambient temperature variations. 中文

Table 1. Calorimetry results

(a) FPH Calorimeters: current 300 mA, current density 80–110 mA cm ⁻² , 0.1 M LiOH, NaOH, LiOD, NaOD						
Pd ^d		H ₂ O Cells			D ₂ O Cells ^b	
Diameter	Volume	Cation	Mean Joule input ^c (mW)	Excess ^{d,e} (mW)	Mean Joule input ^c (mW)	Excess ^{d,e} (mW)
Surface area	Charging time					
6 mm	0.28 cm ³	Li	820	−45±50	960	12±57
3.9 cm ²	870 h	Na	590	14±71	980	57±44
4 mm	0.19 cm ³	Li	800	−19±28	960	−20±29
3.5 cm ²	810 h	Na	610	−55±53	960	−11±49
2 mm	0.094 cm ³	Li	780	40±53	930	61±26
3.1 cm ²	740 h	Na	620	−12±38	940	36±40
1 mm	0.071 cm ³	Li	830	−46±64	980	43±64
2.8 cm ²	670 h	Na	620	−18±60	980	−4±35
Mean excess	±($\sigma/\sqrt{n}$) (mW) ^f			−18±4 (n = 143)		+21±4 (n = 146)

(b) IHF and isothermal calorimeters: 0.1 M LiOD						
Calorimeter type	Pd		Current (mA cm ⁻²)	Time (h)	Joule input ^c (W)	Excess ^d (mW)
	Type	Total charging time				
	Surface area	Volume				
IHF	2-mm rod ^d	797 h ^f	156	231	2.341	78±77 ^m
			156	206	2.380	27±48
	3.1 cm ²	0.16 cm ³	219	187	3.842	-1±58
			279	173	5.188	-55±101
	Cast ^g	797 h ^f	35	236	2.172	100±40
			36	201	2.219	47±36
	14 cm ²	0.88 cm ³	49	187	3.489	-31±51
			62	173	4.863	-120±86
Isothermal	2-mm rod ^d	284 h ^h	159	284	0.925 ^e	-10±12 ⁿ
	1.3 cm ²	0.063 cm ³				
	Cast beads ^h	355 h ^h	50	7	0.985	33±12
			30	15	0.415	11±11
			70	7.8	1.796	5±12
			20	15	0.214	10±11
			100	8.6	3.405	-5±12
			120	270	4.825	2±13
	5 cm ²	0.5 cm ³	40	8.1	0.675	7±12
			80	5.7	2.311	9±12
			200	4.8	12.314	-10±12
			160	4.1	8.140	-17±12
			220	4.8	14.675	-9±12
	Melt-spun-ribbon ⁱ	74 h ^f	14	74	8.991	64±17
	74 cm ²	0.35 cm ³				
	2-mm rod ^j	323 h ^f	152	70	1.091	7±11
	1.3 cm ²	0.066 cm ³	530	253	10.358	15±14
	8-mm bar ^k	520 h ^f	30	520	8.974	36±15
	28 cm ²	1.5 cm ³				

^a Johnson Matthey (JM) “Specpure”; drawn from sintered stock prepared from high-purity powder.

^b D₂O from Harwell reference stock, contains 13 kBq ml⁻¹ tritium.

^c Mean Joule input power supplied to cell (see Fig. 2 legend). Values for IHF and isothermal calorimeters have been corrected for heat loss that is due to evaporation (see Fig. 1 legend).

^d Excess power = measured cell output power–calculated Joule input power.

^e (Mean ± 1σ) of values calculated after each refilling to the reference level, excluding first 10,000 minutes of polarization (see text).

^f Mean and standard deviation of the mean calculated for all H₂O data points and all D₂O data points.

^g Specially produced material supplied by JM—prepared from cast Pd stock that was argon-arc melted into rod form using a gravity casting process. The rods were subsequently sliced and bent to decrease the loading time required (maximum distance from bulk to surface ~1 mm). The sample was cleaned using acetone, 10% HCl and distilled water.

^h “Specpure” Pd arc melted three times under argon on a water-cooled copper hearth.

ⁱ A variety of ribbons prepared (JM) by melt spinning of cast or sintered Pd. A proportion of the ribbons were heat treated (JM) for 20 min at 100 °C under 10% H₂/N₂. Ribbon thickness, 125µm.

^j Type ^a that was subsequently vacuum degassed at 1,200 °C, and loaded with deuterium at a pressure of 40 bar. The sample was cooled to liquid-nitrogen temperature before transferring to the calorimeter to minimize loss of D₂.

^k Sintered high-purity bar, sliced and bent to decrease the loading time required (maximum distance from surface to bulk ~1 mm).

^l D₂O from Aldrich Chemical Co., contains ~15 kBq ml⁻¹ tritium.

^m Mean and standard deviation of all data points after temperature stabilization: data point every 3 min.

ⁿ Standard deviation given by $\sigma = \sqrt{\sigma_b^2 + \sigma_y^2 + \sigma_c^2}$ where σ_b is the standard deviation of the baseline measurement, σ_y that of the power measurement with the cell running and σ_c is the standard error of estimate of the correction line (see Fig. 1 legend). σ_b and σ_y were typically 6 mW, σ_c was 8.8 mW.

^o Small error in this particular measurement gave rise to the apparent small endotherm.

中文

As we expected, occasional points from both H₂O and D₂O cells lay outside the “control limits” of $\pm 2\sigma$ (Fig. 2c). No points lay outside $\pm 3\sigma$. No cell showed two or more consecutive points outside $\pm 2\sigma$, and the number of points lying above the control limit in the D₂O-cell experiments was no different from that in the H₂O-cell experiments. Therefore, we conclude that, within the experimental error, there was no significant anomaly in the behaviour of the D₂O cells compared with that of the H₂O cells. If, however, the mean power deviation (Table 1a) for all eight of the D₂O cells ($+9.91 \pm 0.47\%$ or 0.021 ± 0.004 W; mean Joule input 0.96 W) is tested against that for all eight of the H₂O cells ($-2.46 \pm 0.72\%$ or -0.018 ± 0.004 W, mean Joule input 0.81 W for LiOH cells and 0.61 W for NaOH cells), it is clearly highly significant. Because no sequence of individual points lay outside the control limits established above, we suspect that there is another, unknown source of error that scales with the input power. This, of course, could be the postulated “fusion effect”, but the magnitude of the effect is commensurate with the errors. The only reliable way of checking this is to construct calorimeters that are free of major sources of errors, and in particular, do not have a sloping

baseline. We therefore also used both isothermal and steady state (heat flow) calorimeters which satisfy this criterion. [中文](#)

We have also analysed in detail the slope of the output curve¹⁰ to look for momentary power pulses on timescales shorter than the interval between calibrated points. If the Joule input remains constant then this slope should not vary. Any sudden or momentary extra power input, q_c , would change the slope by approximately $(k_{sb} + k_{c,0}) q_c / M_0$ (M_0 is the water equivalent of the calorimeter, other symbols defined in Fig. 2 legend). The number of significant deviations from the mean slope was found to be roughly the same for both the H₂O and the D₂O cells. For the whole data set, the largest power excursion for a D₂O cell (6-mm rod) was ~ 45 mW and for an H₂O cell (6-mm rod) ~ 40 mW. These are small compared with the input power. It is certainly clear that no unusually large power pulses occurred. Given the difficulties in operating these calorimeters, very occasional occurrences of small fluctuations cannot be considered as support for a “fusion” hypothesis. [中文](#)

The other two types of calorimeters used in this study are described in Fig. 1 legend and results are given in Table 1b. We explored a range of different preparations of palladium and of current density, up to nearly 600 mA cm⁻². With the improved heat-flow calorimeters (IHF), the sign and magnitude of the power excess varied with Joule input power, but was always $< 5\%$. Expressed in terms of the volume of the palladium cathode, this sets a limit of 100–500 mW cm⁻³. The most accurate calorimeter used was the isothermal calorimeter (minimum-detectable power change ~ 10 mW; minimum-detectable energy in any brief burst ~ 40 J). We analysed these results at four-hour intervals by averaging both the Joule input power and the measured output power over a period of ~ 20 min. Inspection of the data collected every four minutes between the regions of analysis showed no obvious signs of any short heat “bursts” and we found no trend with time of the

measured output power under any of the conditions used. Table 1b shows that we obtained thermal balance to better than 20 mW (24–240 mW cm⁻³ Pd). We observed slight thermal excesses (30–60 mW) during the initial charging period of the palladium beads, and during runs with high-surface-area cathodes at high current: it can reasonably be assumed that a small amount of recombination (4% at most) was responsible for this effect. [中文](#)

Neutron Counting

We investigated the emission of neutrons from a wide range of cells using three different detector systems (Table 2). The large, high-efficiency detector with which most of the neutron measurements were made is an oil-moderated assembly of 56 ¹⁰BF₃ proportional counters configured as 5 concentric rings^{11,12}. The total efficiency for 2.45-MeV d–d neutrons is 44%. We built an automatic cell shuttle mechanism to exchange regularly two nominally identical cells, only one of which was powered. This enabled the background (which is due mostly to cosmic rays, there being no anti-coincidence counter arrangements) and any signal to be counted virtually simultaneously. In operation the cells were exchanged every 5 min, and the data from the 5 rings were recorded separately. Data from a typical run are shown in Fig. 3 as differences in the count rate between the powered and unpowered cell. Although in the particular example shown, two spikes can be seen in the count rate differences from the detector as a whole, it is clear that these spikes are due entirely to the misbehaviour of ring 4, and are therefore spurious. [中文](#)

Table 2. Measured neutron and γ -ray emission rates for cold fusion electrolytic cells

(a) Neutron emission rates								
Cathode			Electrolyte	Anode	Details of electrolysis			Measured neutron yield ^{8f} (n s ⁻¹)
Material	Mass (g)	Surface area (cm ²) ^h			Current (mA)	Typical voltage	Duration (h)	
Pd rod 2mm ^a	3.4	5.7	0.1 M LiOD	Pt wire	360	5	914	These cells monitored initially by low-efficiency n-detectors with lower detection limit of ~ 100 s ⁻¹ . Later moved to a dual-cavity neutron detector ¹⁰ with lower detection limit ~ 2 s ⁻¹ .
Pd wire 1 mm ^a	0.94	3.1	0.1 M LiOD	Pt wire	200 ^g	4	916	
Pd wire 1 mm ^b	0.94	3.1	0.1 M LiOD	Pt wire	200	4	916	
Pd wire 1 mm ^b	1.4	4.7	0.1 M LiOD	Pt wire	300 ^e	5	917	
Pd wire 1 mm ^c	0.47	1.6	0.1 M LiOD	Pt wire	750	11	856	
Pd plate 1 mm ^d	7.5	13.5	1 M LiOD	Pt sheet	2,000	10	307	
Pd foil	0.5	8.0	0.1 M LiOD	Vitreous C	400–120 ^f	4–20	142	No detected n-emission.
Pd/ ²² Ag ^e	1.6	3.8	0.1 M LiOD	Pt wire	380	5	859	
Pd/ ²² Ag ^e	1.6	3.8	0.1 M LiOD	Pt wire	380 ^g	5	547	

(a) Neutron emission rates								
Cathode			Electrolyte	Anode	Details of electrolysis			Measured neutron yield ^{6f} (n s ⁻¹)
Material	Mass (g)	Surface area (cm ²)			Current (mA)	Typical voltage	Duration (h)	
Pd foil ^f	0.075	1.0	0.1 M LiOD	Pt wire	30	3	87	-0.019±0.042
Pd foil ^g	0.075	1.0	0.1 M LiOD	Pt wire	250	7	6	0.00±0.08
Pd foil ^h	0.075	1.0	0.1 M LiOD +17 mM Na ₂ S	Pt wire	250	7	16	0.04±0.11
Pd foil ⁱ	0.075	1.0	0.1M LiOD	Pt wire	250	8	16	0.005±0.063
Pd foil ^j	0.075	1.0	0.1 M LiOD	Pt wire	250	8	16	0.051±0.061
Pd foil ^k	0.075	1.0	0.1 M LiOD	Pt wire	1,000	15	56	0.068±0.061
Pd foil	0.63	8.0	0.1 M LiOD	Pt foil	1,000	14	17	-0.110±0.082
Pd foil	0.63	8.0	0.1 M LiOD	Pd foil	1,000	18	22	0.012±0.079
Pd ribbon ^l	0.45	0.92	0.1 M LiOD	Pd foil	600 ^e	15	110	-0.063±0.096
Pd foil	0.60	8.0	0.1 M LiOD	Au wire	1,000	12	43	0.068±0.058
Pd pellet ^m	3.0	2	0.1 M LiOD	Pt foil	650	18	68	0.007±0.042
Pd pieces ⁿ	4.4		0.1 M LiOD	Pd foil	500	8	88	0.012±0.033
Pd pieces	4.4		0.1 M LiOD	Pd foil	500	15	88	0.003±0.046 ^s
Ti foil	0.038	1.0	0.1 M D ₂ SO ₄	Au wire	250	5	34	-0.091±0.054
Ti foil	0.038	1.0	0.1 M D ₂ SO ₄	Au foil	1,000	5	3	-0.22±0.12 ^f
(continued)			0.1 M D ₂ SO ₄ +0.02M PdCl ₂		1,000	5	4	-0.22±0.12 ^f
Ti rod	2.2	4.3	Jones ^g	Au foil	100	4	3	-0.06±0.15 ^f
(continued)					500	6	2	-0.42±0.21 ^f
Ti granules ^a	0.5		0.1 M D ₂ SO ₄	Pt wire	250	7	22	0.00±0.072
Ti granules	0.5		0.1 M D ₂ SO ₄ +3 mM Na ₂ P ₂ O ₇	Pt wire	250	7	66	0.044±0.054
Ti granules	40		0.1 M D ₂ SO ₄	Pt wire	250	25	22	-0.009±0.058
Ti granules	40		0.1 M D ₂ SO ₄ +3 mM Na ₂ P ₂ O ₇	Pt foil	250	25	22	-0.010±0.060
Ti granules	17		Jones	Au foil	500	26	24	0.021±0.054
Ti granules								
Ti/6Al/4V	2.8	15.0	0.1 M D ₂ SO ₄	Pt wire	670	5	87	-0.003±0.031 ^s
Ti/6Al/4V ^g	2.7	14.3	0.1 M D ₂ SO ₄	Pt wire	660	5	19	0.031±0.044 ^s
TiFe granules	1		0.1 M D ₂ SO ₄	Pt foil	250	8	24	0.12±0.06
CeAl ₃ granules	11		0.1 M LiOD	Pt foil	500	22	22	-0.051±0.056
UPt ₃ granules	57		0.1 M LiOD	Pt foil	500	20	94	0.10±0.06
(b) γ-ray emission rates								
Cathode			Electrolyte ^c	Anode	Details of electrolysis			Measured 5,488-keV γ-ray yield ^{6g} (γ s ⁻¹)
Material	Mass (g)	Surface area (cm ²)			Current (mA)	Typical voltage	Duration (h)	
Pd foil	0.58	7.5	0.1 M LiOH	Pt foil	450	9	45	(-4.9±7.43)×10 ⁻³
Pd foil	0.74	9.5	0.1 M LiOH	Pt foil	510	9	164	-0.011±0.004
Pd sheet	7.7	12.9	0.1 M LiOH*	Pt foil	200	4.6	50	-0.017±0.012
Pd rod	3.1	2.3	0.1 M LiOH	Au foil	1,000	26	17	0.008±0.011

(b) γ -ray emission rates								
Cathode			Electrolyte ^z	Anode	Details of electrolysis			Measured 5,488-keV γ -ray yield ^m (γ s ⁻¹)
Material	Mass (g)	Surface area (cm ²)			Current (mA)	Typical voltage	Duration (h)	
Ti foil	0.089	2.0	Jones*	Au foil	320	5	42	-0.022±0.011
Ti foil	2.2	32	Jones	Au foil	1,000	4	12	-0.015±0.034
Ti foil	2.2	32	Jones	Au foil	1,000	4	6	0.012±0.007
Ti granules	25		Jones	Au foil	710	13	8	0.032±0.036
Ti granules	25		0.1 M H ₂ SO ₄	Au foil	400	20	25	-0.019±0.018
Ti granules	25		0.1 M H ₂ SO ₄	Au foil	765	16	16	0.017±0.022
UPt ₃ granules	42		0.1 M LiOH	Pt foil	300	31	166	(3.1±6.0)×10 ⁻³

^a Cells provided by M. Fleischmann. Cathodes analysed for H, D after use—results H/Pd: 0.01, 0.02 D/Pd: 0.84, 0.72.

^b Cathode wound into a tight spiral. Examined initially in the large n-detector, without shuttle, for 147 h with estimated detection limit 1 n s⁻¹ and a further 5 h with detection limit 0.2 n s⁻¹. Surface of cathode then rubbed with S before further use.

^c Cathode cleaned with emery paper after 300 h.

^d Cathode examined initially in the large n-detector, without shuttle, in 0.1 M LiOD for 183 h; estimated detection limit 1 n s⁻¹. Abraded with 400-grit SiC paper before use.

^e Tubes from D storage system for Tokamak.

^f Cathode analysed for H, D after use—results: H/Pd: 0.03 D/Pd: 0.80.

^g Electrolyte of the above run reused.

^h Cathode and electrolyte of the above run reused; Na₂S added as concentrated aqueous solution.

ⁱ Foil vacuum degassed 1,000 °C before use. Analysed for H, D after use—results: H/Pd: 0.02 D/Pd: 0.83.

^j Foil dipped in Na₂S (concentrated solution) before use. Analysed for H, D after use—results: H/Pd: 0.05 D/Pd: 0.80.

^k Cathode cut in half and analysed for H, D after use—results: H/Pd: 0.02, 0.02 D/Pd: 0.85, 0.78.

^l Melt-spun ribbon provided by Johnson-Matthey Technology Centre.

^m Arc remelted twice; electrolytically charged for 1 month in 0.1 M LiOD then frozen in liquid nitrogen, dipped in concentrated Na₂S solution and transferred to n-counting cell.

ⁿ Four 1–2-mm-thick discs of different types of Pd (Johnson-Matthey) spot welded to Pd wires plus strained Pd Wire.

^o Electrolyte reused after a previous run with a Ti cathode and Pt anode.

^p Material heated to 900 °C then quenched in water before use.

^q AuCN in Jones electrolyte replaced with NaAuCl₄.

^r Current on for 36 h then changed between 200 mA and 20 mA every hour.

^s Current on for 36 h then changed between 300 mA and 30 mA every 5 min.

^t Current changed slowly over range shown during electrolysis period as anode disintegrated.

^u Current on for 36 h then cycled off for 10 h and on for 2 h for period of 270 h. Then 5,000 s at 380 mA cathodic and 4,000 s at 10 mA anodic for rest of period.

^v Current cycled on/off every 2 h. Neutron yield is for “on” cycle.

^w The errors assigned (1σ , calculated over full run duration) vary somewhat because in an attempt (mostly in the earlier stages of the programme) to cover as wide a range of cell configurations as possible, pairs of unpowered + unpowered and powered + unpowered runs were not always carried out, and consequently allowance has to be made for slight differences in overall cosmic-ray neutron detection efficiencies caused by slight differences between the two nominally identical cells.

^x These data were obtained using a different data acquisition system to drive the shuttle and accumulate data, set up to look for neutron bursts¹⁰.

^y Cells exchanged every 5 min by hand.

^z All electrolytes used for γ -ray work were 50:50 $\text{H}_2\text{O}:\text{D}_2\text{O}$ except * which were 41:59 $\text{H}_2\text{O}:\text{D}_2\text{O}$.

^{aa}For the present measurements, the system was calibrated with a set of standard γ -ray sources and a $^{238}\text{Pu}/^{13}\text{C}$ (α , $n\gamma$) source emitting 6,129-keV γ -rays. The cells were positioned such that their cathodes were as close as possible to the detector crystal, and the detection efficiencies were calculated by integrating previously measured²¹ point efficiency functions over the cathode volume. Peaks were searched for at 5,488, 4,977 and 4,466 keV corresponding to the expected location of the full energy, single-escape and double-escape peaks using the method recommended in ref. 22. 中文

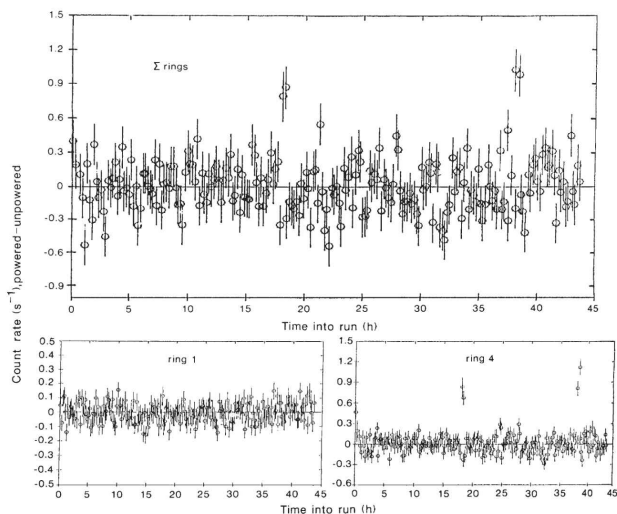


Fig. 3. Data from a typical run on the large high-efficiency neutron detector. These show the differences between count rates for powered and unpowered cells resulting from successive alternate shuttle positions for 40 g of titanium granules in 0.1 M D_2SO_4 . The errors shown are 1σ errors for each five-minute counting period. In addition to results from the detector as a whole, results from two of the five rings of 2-inch diameter 107-cm active length $^{10}\text{BF}_3$ proportional counters are also shown. The counts in rings 2, 3 and 5 (not shown) were very similar to those in ring 1. The apparent bursts were seen only in ring 4 and are therefore a spurious effect. A tube (90-mm inner diameter) passes through the centre of the detector, and the shielding consists of 6 inches of borated resin, 1 mm of cadmium and 2 inches of lead. The neutron detection efficiency is high and is largely independent of neutron energy, varying

from 48% for 0.5-MeV (Am/Li) neutrons to 40% for 4.2-MeV (Am/Be) neutrons. The background count rate is 4–5 count s⁻¹, and most neutrons are from cosmic rays. Each of the five rings of counters has its own independent pre-amplifier, pulse-shaping amplifier and discriminator, and the mean energy of neutrons counted can be obtained from the ratio of counts in the outermost ring of counters (ring 5) to counts in the innermost (ring 1). Because neutron counts are distributed over five rings, and because of the 135-μs-mean time to capture, neutrons emitted simultaneously from a source as a burst are counted separately (as seen with the ²⁵²Cf source, for example). The pre-amplifiers, high voltage components and insulators are all contained within a desiccated electrically screened box, and we eliminate earth loops and induced electromagnetic pick-up (“aerial”) effects from external coaxial cable runs to the PDP-11/45 data-acquisition computer by using isolating high-frequency pulse transformers and by winding the coaxial cables many times around ferrite rings. The neutron detector and its immediately associated electronics are located in a temperature-controlled air-conditioned blockhouse with two-foot-thick concrete walls and roof. [中文](#)

The details of the cells and results of the measurements are given in Table 2. The lowest limits (2σ) on neutron emission derivable from Table 2 for palladium are 1.5×10^{-2} n s⁻¹g⁻¹ or 1.5×10^{-2} n s⁻¹ cm⁻², if the emission were sustained over the whole run. For titanium, the values are 3×10^{-3} n s⁻¹ g⁻¹ and 4×10^{-3} n s⁻¹ cm⁻², although the latter limit is too high because it does not apply to the runs using granules having a large and indeterminate surface area. If we assume the emission to be sustained over only a one-hour period at most, then the limits are, for palladium: 7×10^{-2} n s⁻¹ g⁻¹ or 4×10^{-2} n s⁻¹ cm⁻², and for titanium: 8×10^{-3} n s⁻¹ g⁻¹ or 2×10^{-2} n s⁻¹ cm⁻² (much less in the runs with granules). The neutron-emission rate limits are several orders of magnitude below the rates of $\sim 10^4$ s⁻¹ reported in ref. 1 and about one order of magnitude below the rate of ~ 0.4 s⁻¹ reported in ref. 2. It is significant that the limits in our work were also obtained for cells in which cold fusion could be expected to be enhanced, in particular by using titanium cathodes in the form of a large (40 g) mass of porous granules to increase both the reaction volume and the surface area, and an electrolyte specifically chosen to promote deuterium loading into the cathode¹³ (see Fig. 3). As discussed later, we have not expressed the results in terms of the number of deuterium pairs within metal lattices. [中文](#)

Because the net count rates given in Table 2 are differences between much larger background rates, runs were undertaken with a calibrated ^{252}Cf source (0.024 ± 0.003 fissions s^{-1}) emitting 0.09 ± 0.01 n s^{-1} and a physically identical blank. The result was 0.14 ± 0.05 n s^{-1} , in satisfactory agreement. Furthermore, the expected neutron output of the unpowered Upt_3 cell, which is due to spontaneous fission of ^{238}U , was 0.22 s^{-1} . The value measured in comparison with an empty cell was 0.20 ± 0.06 s^{-1} . Our confidence in the results of the shuttle differences seems justified. Measurements on CeAl_2 and Upt_3 cells were included in the hope that high effective electron masses corresponding to these metal crystal lattices would mimic in some way the fusion enhancement effect of “heavy electrons” such as muons in binding the deuterium nuclei closer together. The palladium ribbon run with the cell power switched on and off every two hours (which was about eight times the characteristic diffusion time in the ribbon) was undertaken to enhance the appearance of non-equilibrium effects, and results (negative) are given in Fig. 4. 中文

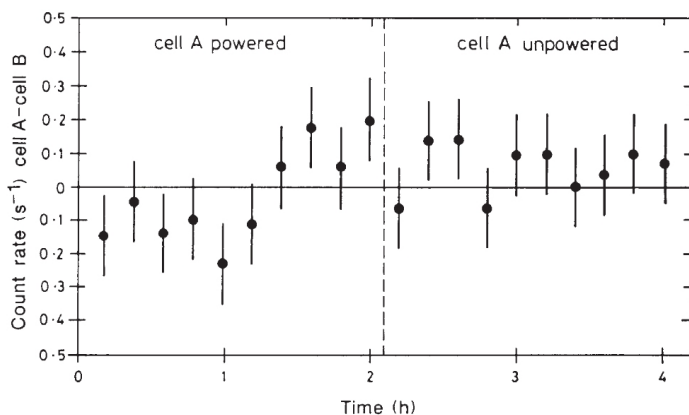


Fig. 4. Time dependence of neutron emission from an electrolytic cell with melt-spun Pd ribbon cathode and Pd foil anode, with power alternately turned on for deuterium loading and off for relaxation every 2 h by the data-acquisition computer: see Table 2 footnote 1. The total length of the run was 110 h, and the sums of the “on” and “off” data are shown. After 90 h of running, we added $1\mu\text{M}$ Pb^{2+} (to poison the surface by Pb deposition) to the solution. There was no difference between the data in the presence and absence of Pb^{2+} , and so data for the whole run was combined. This run was undertaken to enhance the appearance of the non-equilibrium effects discussed in the text. It is assumed that the ribbon would have had a

high density of grain boundaries, dislocations and other lattice defects. Because the “on” and “off” periods were several times the characteristic diffusion time for the ribbon, it is assumed that the composition was cycling in the β -phase region between the fully loaded condition ($D/Pd \approx 0.83$) and the limit of the ($\alpha + \beta$) phase field ($D/Pd \approx 0.65$). 中文

γ -ray Counting

As it has been shown that cold proton-deuteron (p-d) fusion is expected to proceed at rates greater by ~ 8.5 orders of magnitude than d-d fusion³, we carried out an alternative investigation of electrolytic enhancement of hydrogen-isotope fusion by looking for the $D(p, \gamma)^3\text{He}$ 5,488-keV γ -rays from p-d fusion. We used a lead-shielded 113-cm³ n-type high-purity germanium (HPGe) crystal γ -ray spectrometer to search for any γ -rays in the energy range 0.1–7 MeV emitted by a variety of cold-fusion cells operating with a mixture of light and heavy water. The results, also given in Table 2, are consistent with no γ -ray emission. The lowest limits (2σ) on γ -emission derivable from Table 2 are, for palladium, $7 \times 10^{-3} \gamma \text{ s}^{-1} \text{ g}^{-1}$ or $1 \times 10^{-3} \gamma \text{ s}^{-1} \text{ cm}^{-2}$, and for titanium $1.4 \times 10^{-3} \gamma \text{ s}^{-1} \text{ g}^{-1}$ or $4 \times 10^{-4} \gamma \text{ s}^{-1} \text{ cm}^{-2}$, if we assume that the emission is sustained over the whole run. Jones *et al.*² report that the fusion activity may last for only 4–8 h and begin ~ 1 h after the cell is powered, and in these circumstances typical values for the standard deviation in the γ -ray emission rates are $\sim 0.05 \text{ s}^{-1}$ and the 2σ limits for titanium are $4 \times 10^{-3} \gamma \text{ s}^{-1} \text{ g}^{-1}$ or $3 \times 10^{-3} \gamma \text{ s}^{-1} \text{ cm}^{-2}$. Post-run analysis of the hydrogen isotopes taken up by the palladium cathodes with the mixed light and heavy-water electrolytes used gave very satisfactory D:H ratios, lying in the range 1.5–2.5. We note that if the proposed enhancement of the fusion process is as valid for p-d as for d-d fusion then, because of the enhanced tunnelling in the lighter d-p system³, the γ -ray measurements actually provide a much more stringent limit on the cold fusion process than do the neutron measurements. The interpretation of the results from some of these cells was complicated by the dissolution of gold anodes and the consequent gold deposition onto the cathode: this also would have

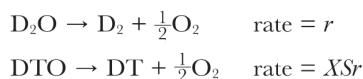
affected the original work². [中文](#)

Tritium Enrichment

Fleischmann *et al.*¹ claimed a tritium production rate of $\sim 10^4$ atom s⁻¹, commensurate with their reported neutron emission rate. They used a differential technique in which the tritium accumulation in a cell with a palladium cathode was compared with that in a cell with a platinum cathode. They took samples for analysis at regular intervals and maintained a constant total electrolyte volume by the addition of fresh D₂O. [中文](#)

Electrolytic enrichment is widely used to increase the concentration of tritium in water before analysis¹⁴. Reproducible results require careful control of the electrolysis, as the enrichment factor can vary widely (refs 15, 16 and R. L. Otlet, personal communication): important effects are seen with change of electrode materials, with variation in the condition (activity) of the electrode surface, with the current density (overvoltage) and with the temperature. Without precautions, the variations in enrichment factor can be more than a factor of two¹⁶. The claims therefore need to be assessed against this known variable electrolytic enrichment. Surprisingly, Fleischmann *et al.*¹ claimed that there was no electrolytic enrichment in their platinum cell. [中文](#)

If the rates of electrolytic evolution of hydrogen isotopes are written as follows



where r denotes the electrolysis rate, S the tritium-deuterium separation factor and X the mole fraction of tritium, T, in the solution, then the tritium accumulation is given by¹⁰

$$\frac{X}{X_0} = \frac{1}{(S+\alpha+\gamma)} \left\{ 1 + \alpha + \gamma - (1-S) \exp \left[- \frac{(S+\alpha+\gamma)rt}{N_0} \right] \right\} \quad (1)$$

where the total solution volume is maintained constant by the addition of fresh D₂O (containing a mole fraction X_0 of tritium, directly proportional to the disintegration rate), the ratio of the sampling rate of the solution to the electrolysis rate is α and γ denotes the ratio of the rate of evaporation of the solution to the electrolysis rate—a small correction that may be calculated assuming that the electrolysis gases passing out of the cell are saturated with water vapour. On the timescales of interest, variability in S would give a variable enrichment

$$\delta\left(\frac{X}{X_0}\right) = -\frac{rt}{N_0} \delta S \quad (2)$$

If the solution becomes contaminated by hydrogen absorption from the atmosphere, then if S_{obs} denotes the apparent DT enrichment factor derived from the application of equation (1), $S_{\text{obs}} = S/[0.5(1 + f)]$, where $f = (1 - X_{\text{H}})/(1 + X_{\text{H}}(S_{\text{HD}} - 1))$ with X_{H} denoting the mole fraction of hydrogen and S_{HD} the HD separation factor (relative rate of reaction of HDO and D₂O). Therefore, as well as the inherent variability from one electrode to another, it is evident that any variability in the amount of hydrogen pickup will give a variation in the apparent enrichment factor:

$$\frac{dS_{\text{obs}}}{dX_{\text{H}}} = \frac{S_{\text{HD}}}{2[1 + X_{\text{H}}(S_{\text{HD}} - 1)^2]}$$

We found that, unless exceptional precautions were taken (and we believe that we used experimental procedures very similar to those used in ref. 1 (M. Fleischmann, personal communication)), values of $X_{\text{H}} \approx 0.07$ were common. Under these conditions, a change of X_{H} of only 0.01 would give a change in S_{obs} of 0.02, which could be significant given the smallness of the claimed effect. 中文

Any assessment of whether differential enrichment can be considered to account for the results in ref. 1 depends critically on the value of

X_0 , which was not reported. Using values¹ of r (1.24×10^{18} atom s⁻¹) and N_0 (14.6×10^{23} atom) we calculate from equation (2) that if X_0 were at the extreme low end of the range for commercial D₂O (3 Bq ml⁻¹), a value of $\delta S = 0.46$ would be required; if it were moderate (10–15 Bq ml⁻¹) a value $\delta S \approx 0.1$ would be needed; if it were high (80 Bq ml⁻¹) $\delta S \approx 0.02$ would suffice. 中文

The applicability of equation (1) was confirmed experimentally, on both platinum and palladium cathodes, in conjunction with calorimetric and neutron-counting experiments (see Fig. 5 legend) using D₂O with an initial tritium content of 13 kBq ml⁻¹ (efficiency corrected). The fit of this equation to all the experimental data (Fig. 5) gave, for palladium, $S_{\text{obs}} = 0.59$, and for platinum, $S_{\text{obs}} = 0.61$. Correction for the uptake of hydrogen, using $S_{\text{HD}} = 6$ (ref. 16), gave $S \approx 0.48$, in agreement with previous work and theoretical expectations ($S = 0.46 \pm 0.02$, (refs 14, 15 and D. S. Rawson and R. L. Otlet, personal communication)). For individual electrodes, S_{obs} for palladium varied from 0.46 to 0.65 (corrected S from 0.42 to 0.58), whereas S_{obs} for platinum varied from 0.56 to 0.85 (corrected S from 0.43 to 0.69)—a total range for individual electrodes of $\delta S_{\text{obs}} = 0.4$, which is enough to account for the results of Fleischmann *et al.*¹.

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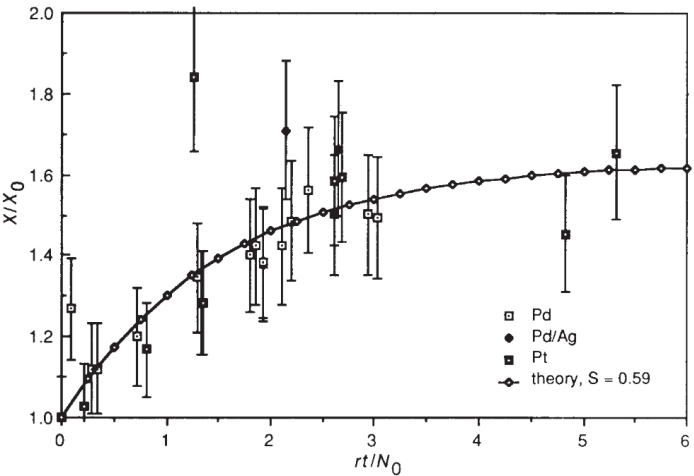


Fig. 5. Tritium enrichment by electrolysis in open cells at constant volume, with both Pd and Pt cathodes: relative count rate X/X_0 against amount of electrolysis rt/N_0 (symbols defined in the text). Initial count rate (efficiency corrected) was 13.0 ± 0.6 kBq ml⁻¹. Errors are 1σ . The Pd cells were the FPH calorimeters, sampled after 490–660 h, the cells in the first section of Table 2 (footnotes *a–e*) sampled at the end of the run and one cell from the high-efficiency neutron detector—footnote *k* in Table 2. The line is the fit to equation (1). [中文](#)

It is clear from these results and discussion that more evidence needs to be presented before the tritium accumulation reported¹ can be considered as experimentally reliable evidence for the occurrence of a fusion process. [中文](#)

Materials Characterization

With 125- μ m palladium foils, hydrogen loadings (determined¹⁰ by hot-extraction mass spectrometry of specimens frozen in liquid nitrogen, and independently by electrochemical extraction) of $H/Pd = 0.95 \pm 0.05$ were achieved in ~ 1 h at 100 mA cm⁻² in 0.1 M LiOH solution with a platinum anode. The limit of deuterium loading in 0.1 M LiOD was lower (0.84 ± 0.03). Rods (1- and 2-mm diameter) polarized for extended periods in neutron counting and calorimetry experiments showed $D/Pd = 0.76 \pm 0.06$. It is well known¹⁷ that the equilibrium pressure for a given deuterium loading is higher than that for the same hydrogen loading. Current-interruption methods confirmed that overpotentials in the range 0.8–1 V (ref. 1) were being obtained. From an initial composition $>99.9\%$ D₂O, the solutions degraded to $\sim 98.5\%$ in 24 h and to 88–98% (analysis by infrared spectrometry) following electrolysis for many weeks. The resulting ratio H/D in the palladium was 0.02–0.04. [中文](#)

During electrolysis, all of the palladium cathodes became covered with a layer that varied in appearance from a dull tarnish to a dense jet black. In the latter case, loose black material was also formed, which in extreme cases came off during electrolysis, resulting in quite heavy erosion of the cathode. The layer itself evidently represented a

modification of the morphology of the cathode at the surface. The formation of a thick black layer was enhanced at high current density, at high temperature, on smaller diameter wire and by frequent abrupt alterations of the current density repeated over a long period. The layer was more noticeable on the outside of a spiral-wound cathode than on the inside. The layer was also more noticeable on cathodes polarized in D_2O than on those polarized in H_2O (perhaps this is related to the greater equilibrium gas pressure for equivalent composition in the Pd-D system), and was different in appearance on materials from different sources. These observations may be explained by the old idea¹⁷ that microfissures, or rifts, develop in palladium to release the mechanical strains resulting from the heavy loading of hydrogen, together with the assumption that any such effect would depend on the stress state of the metal surface and its microstructure.

中文

Lithium was present in the surface layer on cathodes used in LiOD, and analysis by secondary-ion mass spectrometry (SIMS) apparently showed a concentration profile extending about $1\text{ }\mu\text{m}$ into the metal. SIMS images showed that the lithium was not uniformly distributed, however, and it seemed likely that it was trapped in microfissures in the surface layer. 中文

Surface analysis showed a number of other species on and in the surface layer, notably small quantities of platinum and traces of copper, zinc, iron, lead and silicon: platinum would have originated from the anode and silicon from the glass container. No doubt the majority of the other contamination would have come from the solution: the levels found (a few atom percent, confined to the surface layers) were consistent with deposition by extended electrolysis from a solution of concentration around 10^{-9} – 10^{-10}M . One possible criticism is that low levels of such deposition could poison any essential catalytic activity: we therefore used pre-electrolysis in

several experiments, in an attempt to lower the surface contamination. We either made repeat experiments on the same solution, simply changing the cathode, or treated the solution beforehand in a separate cell. [中文](#)

Because of claims that an unusual mechanism might lead to nuclear reactions proceeding predominantly non-radiatively to ${}^4\text{He}$, four cathodes (Table 2, first four entries) were analysed by vacuum fusion/mass spectrometry. The high vapour pressure of palladium at the melting point caused difficulties, so internal standards were prepared by ion implantation of 10^{13} and 10^{15} atoms of ${}^4\text{He}$ into samples cut from the cathodes. Detection limits for ${}^3\text{He}$ and ${}^4\text{He}$ determined in this way were $\sim 8 \times 10^{10}$ atoms per sample— $(1-10) \times 10^{11}$ atom g^{-1} . We found no ${}^3\text{He}$ or ${}^4\text{He}$. The expected level, if fusion had been occurring at the rate reported in ref. 1, was $\sim 10^{16}$ atom g^{-1} . [中文](#)

Evolution of hydrogen at a titanium cathode resulted, as is well known¹³, in a dense network of hydride precipitates, observable by standard metallographic methods, penetrating below the surface. In 0.1 M D_2SO_4 electrolyte at 100 mA cm^{-2} , the network penetrated $\sim 30\mu\text{m}$ in 1 h. Precious-metal deposition inhibited the electrolytic uptake, presumably by lowering the overvoltage and promoting gas evolution. Electrolysis in the “brew” used by Jones *et al.*² resulted in hydride precipitates confined to the grain boundaries; other experiments showed that the presence of PdCl_2 in the electrolyte caused this effect, presumably as a consequence of palladium plating on the cathode. It is clear that expressions of the fusion rate that assume that the cathode has composition TiD_2 are completely misleading: metallography shows that the number of deuterium pairs is far fewer, hence the claimed fusion rate per deuterium pair is far higher than the figure given, and so the results are even more difficult to reconcile with expectations than had been implied². [中文](#)

Discussion

The interest in cold fusion has generated a large number of neutron counting experiments. It is well known that, in general, it is inadvisable to measure the signal + background and background of counting measurements at different times and in different physical locations (as in ref. 1), because of unexpected systematic variations. This is especially true for low-count-rate experiments. Compensating for variation of the background rate and assessing appropriate errors for the procedure chosen are particular problems. The work of Jones *et al.*² can be criticized for such errors¹⁸. It is notable that in ref. 2, only one run in fourteen showed a significant effect and then only because this particular run was assigned a smaller counting error than the others. Here we have attempted to minimize, by the shuttle procedure, uncertainty about background and counter variability and about error calculation. Given some of the more spectacular claims that have been made, we note that further caution is advisable because of the notorious sensitivity of $^{10}\text{BF}_3$ and ^3He proportional counters to humidity and of counter-amplifier systems to earth loops. In our work the neutron detectors were segmented, and the relationship between signals from the segments was well known, so spurious effects giving inconsistent signals from the segments could be identified. 中文

Failure to reproduce the effects has been attributed by some to the need for rigorous exclusion of hydrogen and claims have been made that palladium electrodes must be cast and carefully degassed before use, to remove all traces of carbon and hydrogen impurity which might decorate dislocations or other high-energy sites (ref. 19 and R. A. Huggins, Workshop on Cold Fusion, Santa Fe, May 1989): this is however inconsistent with the postulate of a “fusion” origin for the effect because, at low energies, p-d fusion is expected to be significantly faster than d-d fusion³. Furthermore, the original reports^{1,2} did not mention any special precautions to exclude atmospheric water vapour apart from careful covering of the

electrolytic cells. We followed similar procedures, and found that degradation of the heavy water by exchange with atmospheric moisture occurred quite rapidly. Alternatively, it is claimed that it is essential to maintain a high current density for a considerable period (A. J. Appleby, Workshop on Cold Fusion, Santa Fe, May 1989) although it is not completely clear whether these latter claims are in fact reproductions of the effect reported in ref. 1 or are something different. In our neutron counting experiments, fresh dislocations were introduced by plastic deformation, some counting experiments were carried out at current density as high as 1 A cm^{-2} (Table 2) and in one experiment in the isothermal calorimeter a high current density was maintained for a considerable period (Table 1). Trace deposition of platinum on the cathode, supposedly causing a lowering of the overpotential for deuterium evolution and hence a lowering of the attainable deuterium level in the cathode, has also been suggested as an explanation for irreproducibility (M. Fleischmann, personal communication). We observed no effect when we used palladium anodes in our neutron counting experiments. [中文](#)

Timescales for hydrogen and deuterium loading consistent with the expected diffusion time (x^2/D where the diffusion coefficient, $D = 10^{-7} \text{ cm}^2 \text{ s}^{-1}$ and x is the radius or half-thickness of the specimen) were measured¹⁰ and nuclear counting and calorimetric experiments were always conducted over periods much longer than this. Furthermore, in the process of electrolytic loading of palladium, there will clearly be a concentration gradient, a moving phase boundary and the outer atomic layers of the metal will be saturated (possibly supersaturated) with deuterium¹⁷. It might be expected, therefore, that sufficiently sensitive equipment would detect any fusion process well before the material is completely loaded. Because our neutron detection sensitivity was $\sim 10^5$ – 10^6 times greater than that of Fleischmann *et al.*¹, it seems unlikely that any greatly enhanced fusion process associated with the absorption of deuterium into palladium, giving

rise to neutron emission, is occurring. We are, of course, aware that it is always possible to construct essentially untestable theories involving hypothetical special conditions of the metal or of its surface. Careful characterization of materials for which positive results are claimed is therefore of great importance. [中文](#)

It has been argued that the neutron branch of the d-d reaction might be completely suppressed in favour of the (t + p) branch and it has been further argued (S. Pons, personal communication) that the tritium produced as a result of a nuclear process inside the electrode need not necessarily exchange with the electrolyte and might not therefore be detected. However, the other product of such a nuclear process, a high-energy proton, should be detectable by its interaction with the lattice, including neutron emission: we estimate, knowing the rate of energy loss of the protons and by comparison with (p, n) reaction cross-sections for neighbouring elements, a yield of $\sim 10^{-6}$ neutron per proton, implying a neutron yield in our counting experiments of as much as 10^4 s^{-1} if fusion at the rate reported in ref. 1 were to proceed entirely through the (t + p) branch. [中文](#)

In view of the rather large d-d separations in both PdD and TiD₂, it might be argued that fusion requires some non-equilibrium state in the lattice—perhaps at the α/β phase boundary in palladium or at the tips of the growing TiD₂ needles or at a lattice defect—where the d-d or p-d separation could be greatly reduced. Here we created non-equilibrium situations by pulsing the current but we detected no neutron emission (Fig. 4). [中文](#)

Some explanations of the apparent excess heat production have emphasized recombination processes at catalytic metal surfaces²⁰: apart from occasional explosions, however, which did not result in any detectable neutron emission, we found, by comparison of the volume of water added to maintain the cell volume with the electrolysis charge passed, that this was not a significant effect (in

agreement with others⁹). Recombination in the gas space above the liquid, either on exposed cathode surface or catalysed by colloidal metal particles eroded from the cathode, might however account for some of the observations of bursts of heat recently reported (M. Fleischmann and S. Pons, Electrochemical Society Meeting, Los Angeles, May 1989). In discussing the claims in ref. 1, we prefer to focus on characteristics of the “simple” Fleischman, Pons and Hawkins (FPH) calorimeters, because we have only observed small effects (at the level of the inherent uncertainties), which might mistakenly be claimed as arising from cold fusion, in the one type of calorimeter (FPH type) that has major calibration difficulties. Cells using the same electrode and electrolyte materials operated in calorimeters that did not have these problems exhibited none of these effects. 中文

There are two points regarding the calibration that could have a profound effect on the apparent results obtained with FPH-type calorimeters: the first concerns when the calibration is performed and the second how it is performed. Concerning the first point, it seems from our work and that of Lewis *et al.*⁸ that a calibration performed during the first 10,000 min of electrolysis could be seriously in error and lead to an erroneous conclusion that subsequently, rather than being in balance, the cells were exothermic. Concerning the second point, Fleischmann *et al.*¹ describe calibration using the internal-resistance heater, by measurement of Newton’s-law-of-cooling losses. Typically, this procedure might involve the application of power to the heater while electrolysis was occurring, following the temperature-time trace until a steady state was obtained, then switching the heater off and following the cooling curve. This procedure gives an approximation to the differential calorimeter constant, $k_d = d(\Delta P)/d(\Delta T)$ (where P is power and T is temperature) at the operating temperature of the cell and can give rise to errors in two ways. First, because any calibration sequence would require 5–10 h, extrapolation would be required to obtain the correct value at the

reference liquid level: an estimated error of 20% or more could result. Furthermore, because the evaporation of the cell contents increases markedly with increasing temperature, the baseline slope would increase with increasing temperature and the effects of this sort of error would become correspondingly more marked: the claimed effects were indeed greatest in the cells run at the highest input power. Second, these calorimeters are nonlinear (equation (3), Fig. 2 legend), with the effect being significant when the temperature gradient is large: they cannot be described by a simple Newton's-law-of-cooling constant. If a differential calorimeter constant is used to derive the input power, the calculated output would be (from Fig. 2 legend, equation (3))

$$P_{app} = k_d \Delta T = (k_{sb,0} + k_c) \Delta T + 3(k_{sb,0}/T_0) (\Delta T)^2$$

so that, in comparison with the correct output (equation (3))

$$P_{app} - P = 3k_{sb,0}(\Delta T)^2/2T_0$$

If the power applied to the heater is significant compared with the electrolysis power then this error will be even greater. Back calculation from the data given in ref. 1 shows that the claimed effects were largest for Joule input powers on the order of 6 W. For our FPH-type calorimeters, this would have given $\Delta T \approx 50\text{--}60^\circ\text{C}$. Therefore, had these cells been calibrated in this way, an apparent heat excess on the order of 0.8–1 W would have been observed. Our method of calibration (see Fig. 1 caption) considerably reduced the effect of these sources of error. The original report¹ was clearly preliminary in nature, and it is evident from the above that the claims made therein cannot be assessed in the absence of a detailed description of the experimental procedure used and of the methods used to compensate for the systematic errors inherent in the use of a simple calorimeter.

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We feel that our work has served to establish clear bounds for the

non-observance of cold fusion in electrolysis cells, under carefully controlled and well understood experimental conditions and using well characterized materials. Further details are given in ref. 10. Claims of observations of cold fusion ought now to meet similar standards of data analysis and materials characterization so that a proper assessment can be made. 中文

(342, 375-384; 1989)

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Received 8 August; accepted 16 October 1989.

References:

1. Fleischmann, M., Pons, S. & Hawkins, M. *J. electroanal. Chem.* **261**, 301-308 (1989); erratum **263**, 187 (1989).
2. Jones, S. E. *et al. Nature* **338**, 737-740 (1989).
3. Koonin, S. E. & Nauenberg, M. *Nature* **339**, 690-691 (1989).
4. Sun, Z. & Tomanek, D. *Phys. Rev. Lett.* **63**, 59-61 (1989).
5. Leggett, A. J. & Baym, G. *Nature* **340**, 45-46 (1989).
6. Gai, M. *et al. Nature* **340**, 29-34 (1989).
7. Zeigler, J. F. *et al. Phys. Rev. Lett.* **62**, 2929-2932 (1989).
8. Lewis, N. *et al. Nature* **340**, 525-530 (1989).
9. Cunnane, V. J., Scannell, R. A. & Schriffirin, D. J. *J. electroanal. Chem.* **269**, 163-174 (1989).
10. Williams, D. E. *et al. Harwell Report AERE R-13606* (HMSO, London, 1989).
11. Edwards, G., Findlay, D. J. S. & Lees, E. W. *Ann. Nucl. Energy* **9**, 127-135 (1989).
12. Lees, E. W., Patrick, B. H. & Bowey, E. M. *Nucl. Instrum. Meth.* **171**, 29-41 (1980).
13. Fouroulis, Z. A. *J. electrochem. Soc.* **128**, 219-221 (1981).
14. Östlund, H. G. & Werner, E. in *Tritium in the Physical and Biological Sciences* Vol. 1, 95-104 (Int. Atomic Energy Agency, Vienna, 1962).
15. Kaufmann, S. & Libby, W. F. *Phys. Rev.* **93**, 1334-1337 (1954).
16. von Buttlar, H., Vielstich, W. & Barth, H. *Ber. Bunsenges phys. Chem.* **67**, 650-657 (1963).
17. Smith, D. P. *Hydrogen in Metals* (University of Chicago Press, 1948).
18. Carpenter, J. M. *Nature* **338**, 711 (1989).

19. Gittus, J. & Bockris, J. *Nature* **339**, 105 (1989).
20. Kreysa, G., Marx, G. & Plieth, W. *J. electroanal. Chem.* **266**, 437-441 (1989).
21. Croft, S. *Nucl. Instrum. Meth. Phys. Res. A* **281**, 103 (1989).
22. Anicin, I. V. & Yap, C. T. *Nucl. Instrum. Meth. Phys. Res. A* **259**, 525-528 (1987).
23. Savitzky, A. & Golay, M. J. E. *Anal. Chem.* **36**, 1627-1639 (1964).

Acknowledgements. We thank Johnson-Matthey (Dr I. McGill and Dr M. Doyle) for assistance and for the loan of special samples of palladium. IMI Titanium (Mr J. R. B. Gilbert) provided titanium and information. We thank the following for assistance: P. Fozard, M. Newan, J. Monahan, R. Morrison, H. Bishop, V. Moore and colleagues, J. Asher, P. W. Swinden, A. M. Leatham, R. A. P. Wiltshire, D. A. Webb, J. O. W. Norris, R. Roberts, R. Crispin, C. Westcott, R. Neat, D. Robinson, H. Watson and G. McCracken. We also thank Dr D. Schriffrin, Dr P. T. Greenland and Dr D. Morrison for discussions and Dr R. Bullough for support. This work was financed by the Underlying Science programme of the UKAEA, and UK department of Energy and the Commission of the European Communities.

电解池中“冷核聚变”的上限

威廉斯等

当电化学家马丁·弗莱施曼和斯坦利·庞斯宣称他们的小瓶的电解含盐重水中发现了“冷”核聚变的证据时，世界各地很快出现了一些证实其成功或失败的相矛盾的报告。这篇来自英国化学家戴维·威廉斯和他的合作者的文章是首篇将流行观点转向认为冷核聚变只是错觉的文章之一。文章报告了对弗莱施曼和庞斯实验结果的一次非常全面的重复尝试，结果发现没有“过热”、中子发射或者氦生成的证据，而后两者被认为是氘发生聚变的判据。 [英文](#)

使用三种不同设计的量热计、高效率的中子和 γ 射线探测装置对多种材料进行研究的实验未能支持最近弗莱施曼等人^[1]和琼斯等人^[2]关于冷核聚变的声明。可能是一些未探测到的虚假效应导致了这一关于冷核聚变的断言，其中包括中子计数器的噪声、宇宙射线本底的变化、简易量热计的标定误差和可变的氘的电解富集。 [英文](#)

最近发表的论文^[1,2]报道了室温下电化学引发的核聚变，该结果引起了极大的关注。报道中发生核聚变的鲜明特征是配有钨阴极的电解池中过剩的热量输出、中子（即 n ）发射和氦（即 t ）的产生^[1]，以及配有钛阴极的电解池中仅有很低水平的中子发射^[2]。传统核物理预测轻核之间的聚变需要非常高的温度（如在托卡马克装置中那样）或者两个核异常接近（如在 μ 子催化核聚变中那样）。根据氘（即 d ）分子的核间距（ $0.74 \text{ \AA}$ ）计算出的核聚变速率约为 $3 \times 10^{-64} \text{ s}^{-1}$ （参考文献3），所以在已知间隙位间距（约为 $3 \text{ \AA}$ ）的情况下，很难理解参考文献2报道的反应速率（每对氘核每秒约产生 10^{-23} 次聚变效应），如果考虑到氘在钛中并未完全充满（参见材料表征部分），这一速率（约为 $3 \times 10^{-64} \text{ s}^{-1}$ ）还

是被大大低估了，参考文献2中的速率就更不易理解了。而参考文献1中报道的反应速率甚至更难理解^[4]，尽管有强大的反对意见（如参考文献5），他们还是假定存在一种未知的机理，可以使反应速率异常增加，并抑制正常的核反应通道。 [英文](#)

第一批电解冷核聚变效应的报道指出，该效应并非自始至终都是可重复的，它耗时少许才出现并可能随后消失。因为电化学现象对表面状态非常敏感，一些不可重复性本身并不令人惊奇，最近其他的报道（如参考文献6~8）在观察所谓的冷核聚变效应时给出了失败和成功的完备记录（哈金斯和阿普尔比，冷核聚变专题讨论会，圣菲，1989年5月）。重复性的明显缺乏使得效果显著的重复实验变得很有必要，要想使结果具有较高的置信水平，对照实验至少在数目上应该与之前的实验相当，同时要探究许多不同的、特性明确的材料和电解液组合。尤其是钽电极和钛电极电解法充气的时间尺度、可达到的浓度，氢“杂质”的量化，以及在用过的阴极上通过表面分析可以检测到的各种物质都应该测定。 [英文](#)

量热法

我们使用了三种量热计。首先，我们构建了与弗莱施曼等人所用的（参考文献1；弗莱施曼，个人交流）尺寸和设计相似的量热计（图1）。我们发现这种量热计是不精准的装置，具有一些不太容易被发现的误差来源，很有必要对其进行仔细研究和分析。我们使用了16个这样的电解池，包括不同尺寸的阴极（1 mm、2 mm、4 mm和6 mm的钽棒）和不同的电解液（0.1 M LiOD，0.1 M LiOH，0.1 M NaOD或者0.1 M NaOH）。图2a和2b显示了其中一个典型的电解池获得的结果。一个直接的明显特征是具有锯齿状形式的倾斜基线，这是电解池定期地添加电解液的结果。基线的斜率可以通过仪器常数 k 随电解池中液面水平的变化定量地求出。这是由杜瓦瓶内的真空夹层的热辐射损失^[9]和电解池玻璃内壁的热传导^[10]产生的结果（见图2的图注）。基线倾斜的结果就是任何标定只有针对特定的液面水平才是有效的。我们定期将这些电解池重新灌注到进行标定时参考水平。在电解开始前，我们用加热器对电解池进行标定，电解期间，运行了相当一段时间后再标定一次，如图2a所示（标定过程的细节见图1的图注）。两种标定设置没有统计学上

的显著差异，所以我们将所有的数据都结合起来了。 英文

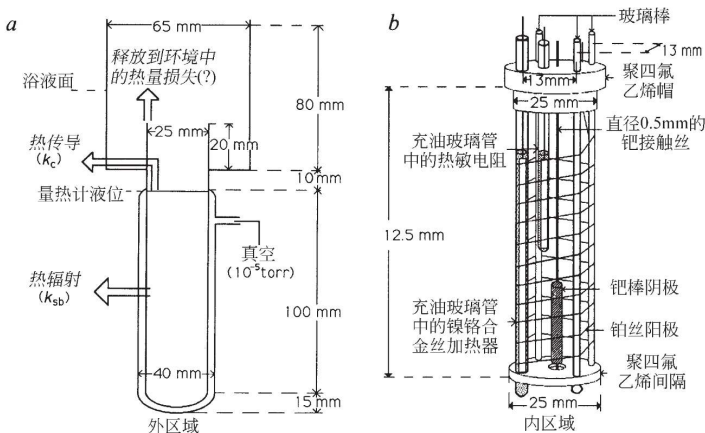


图1．本文使用的FPH型热流量热计示意图。在图中标出了热流的路径，更进一步的讨论如图2的图注所示。

方法：除了弗莱施曼、庞斯和霍金斯（FPH）型的量热计之外，我们还使用了^[10]两种其他类型的量热计——改进的热流量热计（IHF）和等温式量热计。IHF量热计与FPH量热计的不同主要表现在三个方面。首先，IHF量热计更大：500 ml容积的柱状容器构成了电解池，其中阳极-阴极间距约为2 cm。其次，电解容器被塞进一个紧密贴合的铝罐中，用一层油膜保证热接触，铝罐被隔热材料包裹起来并放入一个杜瓦瓶中。FPH量热计中电解池的温度是通过浸入电解池内的、由玻璃保护的热敏电阻进行测量的，而在IHF结构中，测量的是铝罐的温度：对于将电解池中的热量传导出去的过程而言，罐体可以被认为是一个恒温的表面，将它作为温度测量表面解决了FPH结构中基线倾斜的问题。第三，将杜瓦瓶中电解容器上方的空间用一个高高地伸出到杜瓦瓶上方的聚苯乙烯盖子填满，这样做的目的是显著减小未知的释放到大气中的热量损失。两种类型的热流量热计都在水浴中运行，水浴控制在恒定的温度20 °C(±0.08 °C)。水浴的顶部用一个聚苯乙烯的盖子盖住。在两种量热计中，电解池均包括一个弯成螺旋形的铂丝阳极（0.25 mm）和一个中央的钨阴极（庄信万丰公司）。对FPH电解池我们制备了不同的电解液，它们由电导水（H₂O电解池）或者初始同位素纯度大于99.9%轻微氘化了的D₂O（比活性为13 kBq·ml⁻¹）制成。我们用0.1 M LiOD（D₂O购自奥德里奇公司，测得初始同位素纯度大于99.9%）作为IHF量热计中的电解液。在IHF电解池中，铂和钨的接触丝被封装在玻璃管中，以避免电解产物任何可能的催化复合过程。在后面使用FPH电解池的实验中我们也使用了屏蔽的电极接触丝，但是这对获得的结果没有任何影响。IHF电解池包含一根用绝缘套管覆盖到顶端的钨丝电极，它被放置于距电解池底端四分之三处。这是在向电解池添加或者重复添加液体时用来规定内部液面水平的参照。IHF电解池中更大的电解液体积（300 ml）意味着重复添加仅需要偶尔进行，但是较大的热质则意味着响应会比较慢（时间常数约为12小时）：因此他们对热量的少量释放并不敏感。我们用置于填满油的玻璃管中的镍铬合金丝加热器对热流量热计进行了标定，该玻璃管与电解池的内容物相接触。标定的过程包括运行加热器，不施加电解电流或者施加显著小于（0.2~0.4倍）通常电解所需的电流，直到体系获得一个稳态的温度。对于FPH电解池，使用较小的电解电流旨在确保持续搅拌的同时减小由于基线漂移带来的误差；在每次单独的标定之前电解池都要再添加一次电解液。利用方程 $P = a - b(\log R) + c(\log R)^2$ 将得到的热敏电阻的阻值R在应用的功率P的范围内对P进行拟合，其中a，b和c是拟合参数，这样一条经验的标定曲线就得

到了。对拟合曲线估算出的FPH电解池的标准误差在10 mW到高达70 mW之间变化，这主要反映了外推到参考水平时的误差。中子计数使用了安装在电解池上方、水浴盖顶部^[10]的两个独立的计数管组合体，是与FPH电解池的运行同时进行的。高于本底的探测灵敏度在电解池中为每秒3个计数。我们没有观察到任何高于本底的信号。等温式量热计（梅森、怀尔德、维克里、胡顿和韦尔斯，第29届核材料管理协会年度会议录，拉斯维加斯，内华达州，1988年6月）包括三个同轴的铝筒，相互之间用一种较低热导率的导热介质隔开。圆筒的温度通过螺旋缠绕在各圆筒上的电加热器来维持。温度通过每个圆筒上的电阻式温度计来控制，该温度计与经典控制软件和圆筒加热器连接在一起。测量室（直径12.5 cm，高26 cm）中的热能产生速率可以通过精确测量供给测量室的电能来确定。我们在测量室温度为 $42 \pm 0.001^\circ\text{C}$ 的条件下运行量热计。运行功率为20 W时，测量室的功率分辨率小于5mW。电解池中含有约1 L 0.1 M的LiOD。阴极置于一个打孔的盖状玻璃中，以阻止产生的气体在测量室中混合。阳极是一个绕着阴极的高3 cm、直径12 cm的铂箔圆筒。电解池与量热计的测量室通过导热油进行热耦合。使用铂阴极以及镍铬铁合金丝加热器测量，测量结果显示量热计中存在一个小的系统误差，表观的功率过剩随输入功率呈线性变化，输入功率为15 W时，功率过剩高达100 mW。将这些测量值（12个点，估计值的标准误差为8.8 mW）的线性拟合用于对钽阴极所测表观过剩的校正。再对等温式和IHF电解池所测的输出功率进行功率损失校正，功率损失是由于电解液的挥发造成的，假设当电解气体流出电解池（ 42°C 时为 $25.0 \text{ mW}\cdot\text{A}^{-1}$ ）时电解气体在水蒸气中已达到饱和： $q_v = (p_v/p_0)(1.5)\Delta H_v I/(2F)$ ，其中 q_v 为功率损失， p_v 代表饱和蒸气压， ΔH_v 为电解液挥发的相变潜热， p_0 为大气压， F 为法拉第常数， I 为电流（假设为理想气体）。 英文

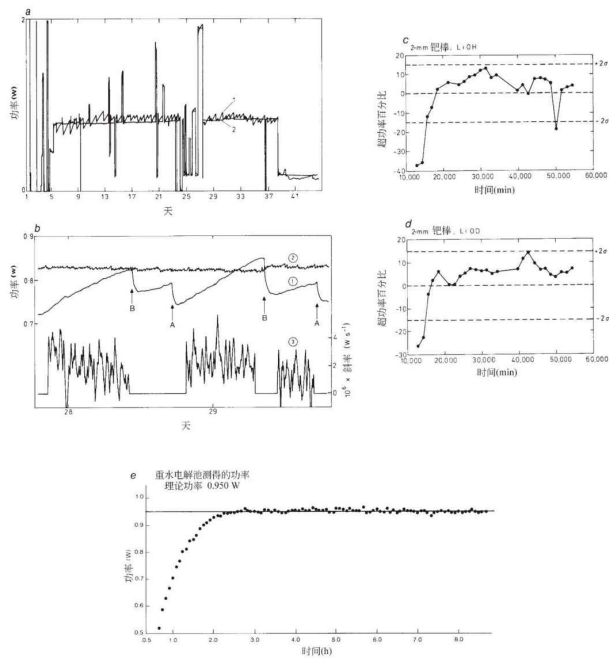


图2 . a，从LiOH电解液中带有一个4 mm钽棒（1.5 cm长，庄信万丰公司的“光谱纯”样品，从熔融态得到）的FPH型量热计得到的原始数据。线1表示根据温度计读数计算出的输出功率，线2表示电解池的焦耳输入功率， $P_{in} = I(V - V_0)$ ，其中 $V_0 = \Delta H_d/2F$ （对于 D_2O 为1.527 V， H_2O 为1.481 V， ΔH_d 为解离焓，例如， $D_2O(l) \rightarrow D_2(g) + 1/2O_2(g)$ ）。大的台阶式变化为标定值。b，a的一个放大区域，突出了倾斜的基线。线1和线2与a中相同。线3是使用七点赛威特斯基-高

勒程序^[23]对数据取微分计算出的表观输出功率的斜率，一步一个点。在点A，将预热到电解池温度的水添加到量热计的参考标记处。在点B，添加进根据电解速率估算的一定体积的液体。*c*和*d*，两个最为一致的FPH型量热计的结果——0.2 cm×3 cm的铂棒在（1）LiOD和（2）LiOH中——以表观输出功率超出焦耳输入功率的百分比形式表示。误差棒代表从所有不同的电解池中所得的结果计算出的控制极限±2σ（见正文）。*e*，使用等温式量热计（20 mm×2 mm直径的铂阴极）得到原始数据，应用输入功率后立即开始测量，曲线代表焦耳输入功率，点代表观察到的电解池功率。这个量热计的响应时间由电解池内容物取得热量混合的时间决定，尽管具有较大的溶液体积，它仍快于简单量热计的响应时间。

倾斜的基线“简易的”FPH型量热计的响应可以模型化为^[10]

$$P_{in} = k\Delta T = (k_{sb} + k_c) \Delta T \quad (3)$$

其中^[9]

$$k_{sb} = \sigma A_1 [T_1^4 - T_0^4] / \Delta T \approx 4\sigma A_1 T_0^3 [1 + 3\Delta T / (2T_0)] = k_{sb,0} (1 + 3\Delta T / (2T_0)) \quad (4)$$

同时^[10]

$$k_c \approx \kappa A_2 / l = \kappa A_2 / (l_0 + IV_m \delta t / (2F\pi r_i^2)) \approx k_{c,0} (1 - \alpha \delta t)$$

（其中 P_{in} 是焦耳输入功率， k 是量热计常数， k_{sb} 和 k_c 分别为通过杜瓦瓶内的真空夹层的辐射损失和沿玻璃内壁的传导对量热计常数的贡献， σ 为斯特凡—波尔兹曼常数， A_1 为溶液与电解池壁的接触面积， T_0 为水浴温度， T_1 为电解池的温度， $\Delta T = T_1 - T_0$ ， κ 为玻璃的热导率， l 为液体到玻璃内壁与水浴的接触点间的距离，它的初始值为 l_0 ， A_2 为玻璃内壁的横截面积， I 为电解池电流（300 mA）， V_m 为电解池溶液的摩尔体积， δt 是从添加电解液后算起的时间， r_i 为玻璃容器的内半径， $\alpha = IV_m / (2F\pi r_i^2 l_0)$ ）。我们测量的电解池的量热计常数约为0.1 W·K⁻¹，是通过方程（4）计算的，这表明 k_{sb} 和 k_c 的贡献大致相当。要对量热计进行更完整的描述就必须考虑溶液损失对量热计热容的影响。然而，可以证明这对倾斜基线的影响是无足轻重的^[10]。 [英文](#)

图2c显示了两个量热计的液面水平都在同一个标定面时的结果，以表观输出功率超过焦耳输入功率的百分比表示。实验开始时有一个明显的吸热反应阶段，这个阶段随阴极直径变大而延长。我们推测在阴极吸氢过程中搅拌不充分是原因之一，因为它在电解池中造成了一个温度梯度（电解开始时并无气体从阴极放出，为了保持表面积不变，直径较大的阴极更短一些）。电解开始时一个类似的效应由刘易斯等人^[8]报道过，他们指出类似的电解池的表观传热系数在实验的初始阶段会变化。由于这个效应，我们在进行统计计算时排除了每个电解池开始运行的前10,000分钟的数据。表1a显示了每个电解池的平均绝对功率偏差值和这个值的标准偏差。所有H₂O电解池的标准偏差同D₂O电解池的没有明显

差异（*F*检验，1%的水平），所以所有电解池的数据都可以用于估算误差： $\sigma = 0.048 \text{ W}$ （即 $\pm 5\% \sim 10\%$ ）。对这个误差进行更加详细的分析[10]，揭示了它主要由重新灌注电解池后液面水平的变化决定，也有由量热计壁向水浴上方空气传导造成的热量损失这一未经量化的变化量的贡献。与这些误差相比，电解池内的温度梯度产生的影响很小。本文中使用的設計不同于参考文献1，我们用玻璃套筒来支撑量热计，而且玻璃套筒与内壁直接接触，由此玻璃套筒就可与水浴有较大面积的热接触，进而减小了室温变化的影响。

英文

表1. 量热法结果

(a) FPH 量热计: 电流 300 mA, 电流密度 80~110 mA · cm ⁻² , 0.1 M LiOH、NaOH、LiOD、NaOD						
Pd ^a		H ₂ O电解池			D ₂ O电解池 ^b	
直径	体积	阳离子	平均焦耳输入 ^c (mW)	过剩 ^{d,e} (mW)	平均焦耳输入 ^c (mW)	过剩 ^{d,e} (mW)
表面积	运行时间					
6 mm	0.28 cm ³	Li	820	-45 ± 50	960	12 ± 57
3.9 cm ²	870 h	Na	590	14 ± 71	980	57 ± 44
4 mm	0.19 cm ³	Li	800	-19 ± 28	960	-20 ± 29
3.5 cm ²	810 h	Na	610	-55 ± 53	960	-11 ± 49
2 mm	0.094 cm ³	Li	780	40 ± 53	930	61 ± 26
3.1 cm ²	740 h	Na	620	-12 ± 38	940	36 ± 40
1 mm	0.071 cm ³	Li	830	-46 ± 64	980	43 ± 64
2.8 cm ²	670 h	Na	620	-18 ± 60	980	-4 ± 35
平均过剩	±(σ/√ <i>n</i>)(mW) ^f			-18 ± 4 (<i>n</i> = 143)		+21 ± 4 (<i>n</i> = 146)

(b) IHF 型和等温式量热计: 0.1 M LiOD						
量热计类型	Pd		电流 (mA·cm ⁻²)	时间 (h)	焦耳输入 ^c (W)	过剩 ^d (mW)
	种类 表面积	总运行时间 体积				
IHF	直径 2 mm 的钯棒 ^a	797 h ^f	156	231	2.341	78 ± 77 ^m
			156	206	2.380	27 ± 48
	3.1 cm ²	0.16 cm ³	219	187	3.842	-1 ± 58
			279	173	5.188	-55 ± 101
	铸造 ^g	797 h ^f	35	236	2.172	100 ± 40
			36	201	2.219	47 ± 36
	14 cm ²	0.88 cm ³	49	187	3.489	-31 ± 51
			62	173	4.863	-120 ± 86
等温式	直径 2 mm 的钯棒 ^a	284 h ^b	159	284	0.925 ^o	-10 ± 12 ⁿ
	1.3 cm ²	0.063 cm ³				
	铸造的颗粒 ^h	355 h ^b	50	7	0.985	33 ± 12
			30	15	0.415	11 ± 11
			70	7.8	1.796	5 ± 12
			20	15	0.214	10 ± 11
			100	8.6	3.405	-5 ± 12
	5 cm ²	0.5 cm ³	120	270	4.825	2 ± 13
			40	8.1	0.675	7 ± 12
			80	5.7	2.311	9 ± 12
			200	4.8	12.314	-10 ± 12
			160	4.1	8.140	-17 ± 12
			220	4.8	14.675	-9 ± 12
	熔体快淬带 ⁱ	74 h ^f	14	74	8.991	64 ± 17
	74 cm ²	0.35 cm ³				
	直径2 mm 的钯棒 ^a	323 h ^f	152	70	1.091	7 ± 11
	1.3 cm ²	0.066 cm ³	530	253	10.358	15 ± 14
	直径8 mm 的钯棒 ^a	520 h ^f	30	520	8.974	36 ± 15
	28 cm ²	1.5 cm ³				

^a 庄信万丰公司 (JM) 的“光谱纯”; 由高纯粉末制备的烧结块料拉制而成。

^b 购自哈韦尔公司的D₂O, 含13 kBq·ml⁻¹的氚。

^c 提供给电解池的平均焦耳功率 (参见图2的图注)。IHF和等温式量热计的数值都就蒸发产生的热量损失进行了校正 (参见图1的图注)。

^d 过剩功率 = 测量的电解池输出功率 - 计算的焦耳输入功率。

^e 在每一次将液面加至参考液面时算出的数值 (平均值 ± 1σ), 排除了开始10,000分钟极化过程的数据 (见正文)。

^f 所有H₂O和D₂O数据点的平均值和平均值的标准偏差。

^g 由JM提供的特制材料——从库存的铸造钯制备得到, 使用一种重力铸造工艺通过氩弧将之熔化成棒状。棒随后被切成片, 并弯曲以减少所需的吸附时间 (从体相到表面的最大距离约1 mm)。样品用丙酮、10%的盐酸和蒸馏水清洗。

^h “光谱纯”的钯在一个水冷的铜炉床上, 在氩气保护下用电弧熔融三次。

ⁱ 由铸造或者烧结的钯通过熔体快淬制备得到 (JM) 的各种快淬带。一部分带经过了在含氩10%的氮气下20分钟100 °C的热处理。带的厚度为125 μm。

^j a型随后在1,200 °C下进行真空除气处理，在40巴的气压下吸附氘。转移到量热计之前样品被冷却至液氮的温度，以减少D₂的流失。

^k 烧结的高纯度铍棒被切成片并弯曲，以减小所需的吸附时间（表面到体相的最大距离为约1 mm）。

^l 购自奥尔德里奇化学品的D₂O，约含15 kBq·ml⁻¹的氚。

^m 所有数据点的平均值和标准偏差都在温度稳定后采集：每3分钟采集一个数据。

ⁿ 标准偏差由公式 $\sigma = \sqrt{\sigma_b^2 + \sigma_y^2 + \sigma_c^2}$ 计算，其中 σ_b 为基线测量的标准偏差， σ_y 为电解池运行时功率测量值的标准偏差， σ_c 为根据校正曲线估算的标准误差（见图1的图注）。 σ_b 和 σ_y 的典型值为6 mW， σ_c 为8.8 mW。

^o这次测量中产生表观少量吸热的小的误差。 [英文](#)

正如我们所预期，H₂O和D₂O电解池给出的数据点都有少量处于 $\pm 2\sigma$ 的“控制界限”之外（图2c）。没有数据点是在 $\pm 3\sigma$ 之外的。所有电解池都没有两个或者更多的连续数据点处于 $\pm 2\sigma$ 之外，D₂O电解池实验中超出控制界限的数据点的数目与H₂O电解池实验并无不同。因此，我们得出结论，在实验误差范围内，D₂O电解池的特性与H₂O电解池相比没有明显的异常。然而，如果根据表1a，将所有8个D₂O电解池（ $+9.91\% \pm 0.47\%$ 或者 0.021 ± 0.004 W；平均焦耳输入0.96 W）与所有8个H₂O电解池的平均功率偏差（ $-2.46\% \pm 0.72\%$ 或者 -0.018 ± 0.004 W，LiOH电解池的平均焦耳输入为0.81 W而NaOH电解池的为0.61 W）进行对比的话，其差别是十分明显的。因为没有一系列的独立数据点处于上述的控制界限之外，我们认为有另外一个未知的误差来源，与输入功率成比例。当然，这可以是假设的“核聚变效应”，但是这个效应的数量级与误差相同。检验这个假设的唯一可信赖的方法就是构建不受主要误差来源影响的量热计，尤其是不倾斜的基线。我们因此也使用了满足这一准则的等温式量热计和稳态（热流）量热计。 [英文](#)

我们也仔细分析了输出曲线的斜率^[10]，以寻找时间尺度上短于校准点间隔的瞬时功率脉冲。如果焦耳输入保持恒定，则斜率应该不变。任何突然或瞬间额外功率 q_c 的输入，都会将斜率改变大约 $(k_{sb} + k_c)q_c/M_0$ （ M_0 为与量热计等效的水的量，其他符号沿用图2的图注中的定义）。H₂O和D₂O电解池中与平均斜率明显偏离的数目大体相同。就所有数据而言，D₂O电解池（6 mm的棒）最大的功率偏移约为45 mW，而H₂O电解池（6 mm的棒）约为40 mW。这些值与输入功率相比较小。很显然没有异常大的功率脉冲出现。鉴于控制量热计的难度，不能将非常偶然的小波动的出现视为是支持“核聚变”假说的证据。 [英文](#)

本研究中使用的另外两种量热计在图1的图注中进行了描述，结果列于表1b中。我们尝试了一系列不同的钷制备方法和最大值接近600 $\text{mA}\cdot\text{cm}^{-2}$ 的一系列电流密度。使用改进的热流量热计（IHF），功率过剩的符号和数量级随焦耳输入功率而变化，但总是小于5%。用钷阴极的体积表示，这个值的范围在100~500 $\text{mW}\cdot\text{cm}^{-3}$ 之间。最精确的量热计是等温式量热计（可探测的最小功率变化约为10 mW ；可探测的任何最小猝发能量约为40 J ）。我们分析这些以4小时为间隔的结果，每约20分钟将焦耳输入功率和测量的输出功率作平均。对分析区域每4分钟获得的数据进行的研究显示，没有任何短时热量“猝发”的明显迹象，而且我们发现在任何我们使用的条件下，测得的输出功率没有随着时间变化的趋势。表1b显示我们获得的热平衡优于20 mW （对钷而言为24~240 $\text{mW}\cdot\text{cm}^{-3}$ ）。在最初的钷电极充电期间以及高表面积阴极在大电流条件下运行的过程中，我们观察到了少量的热量过剩（30~60 mW ）：可以合理地假设是少量的复合过程（至多4%）产生了此效应。 英文

中子计数

我们使用三种不同的检测系统研究了来自多种电解池的中子发射（表2）。我们用大而高效的探测器来进行大部分的中子测量，它是一个由56个 $^{10}\text{BF}_3$ 正比计数器排布成的、由5个同心圆环阵列^[11,12]所组成的装置。2.45 MeV 的d-d中子总效率为44%。我们构造了一个自动电解池滑梭装置来定期调换两个形式上完全相同的电解池，只有其中一个是通电的。这使得本底（本底主要来自宇宙射线，没有布置反符合计数管）和任何信号可以实质上同时计数。操作时，电解池每隔5分钟调换一次，5个圆环上的数据分别被记录下来。从一次典型实验中得到的数据如图3所示，它们是通电和不通电的电解池的计数率之差。尽管在所展示的特例中，从探测器整体的计数率之差可以看到两个尖峰信号，但是这些尖峰信号显然完全是由于环4的错误响应引起的，因而是假象。

英文

表2. 所测的各冷核聚变电解池的中子和 γ 射线发射速率

(a)中子发射速率								
阴极			电解液	阳极	电解细节			测得的中子产率 ^w (个/秒)
材料	质量(g)	表面积(cm ²)			电流(mA)	典型电压	时长(h)	
2 mm 的钯棒 ^a	3.4	5.7	0.1 M LiOD	铂丝	360	5	914	这些电解池最初使用具有较低检测限(约100 s ⁻¹)的低效率中子探测器进行检测。后来又使用一个具有更低检测限(约2 s ⁻¹)的双腔中子探测器 ^[10] 。
1 mm 的钯丝 ^a	0.94	3.1	0.1 M LiOD	铂丝	200 ^r	4	916	
1 mm 的钯丝 ^b	0.94	3.1	0.1 M LiOD	铂丝	200	4	916	
1 mm 的钯丝 ^b	1.4	4.7	0.1 M LiOD	铂丝	300 ^s	5	917	
1 mm 的钯丝 ^c	0.47	1.6	0.1 M LiOD	铂丝	750	11	856	
1 mm 的钯盘 ^d	7.5	13.5	1 M LiOD	铂片	2,000	10	307	
钯箔	0.5	8.0	0.1 M LiOD	玻碳	400~120 ^f	4~20	142	未检测到中子发射
钯银 22 合金 ^e	1.6	3.8	0.1 M LiOD	铂丝	380	5	859	
钯银 22 合金 ^e	1.6	3.8	0.1 M LiOD	铂丝	380 ^u	5	547	

(a) 中子发射速率								
阴极			电解液	阳极	电解细节			测得的中子产率 ^W (个/秒)
材料	质量(g)	表面积(cm ²)			电流(mA)	典型电压	时长(h)	
钽箔 ^f	0.075	1.0	0.1 M LiOD	铂丝	30	3	87	-0.019 ± 0.042
钽箔 ^g	0.075	1.0	0.1 M LiOD	铂丝	250	7	6	0.00 ± 0.08
钽箔 ^h	0.075	1.0	0.1 M LiOD +17 mM Na ₂ S	铂丝	250	7	16	0.04 ± 0.11
钽箔 ⁱ	0.075	1.0	0.1 M LiOD	铂丝	250	8	16	0.005 ± 0.063
钽箔 ^j	0.075	1.0	0.1 M LiOD	铂丝	250	8	16	0.051 ± 0.061
钽箔 ^k	0.075	1.0	0.1 M LiOD	铂丝	1,000	15	56	0.068 ± 0.061
钽箔	0.63	8.0	0.1 M LiOD	钽箔	1,000	14	17	-0.110 ± 0.082
钽箔	0.63	8.0	0.1 M LiOD	钽箔	1,000	18	22	0.012 ± 0.079
钽带 ^l	0.45	0.92	0.1 M LiOD	钽箔	600 ^v	15	110	-0.063 ± 0.096
钽箔	0.60	8.0	0.1 M LiOD	金丝	1,000	12	43	0.068 ± 0.058
钽颗粒 ^m	3.0	2	0.1 M LiOD	钽箔	650	18	68	0.007 ± 0.042
钽片 ⁿ	4.4		0.1 M LiOD	钽箔	500	8	88	0.012 ± 0.033
钽片	4.4		0.1 M LiOD	钽箔	500	15	88	0.003 ± 0.046 ^x
钛箔	0.038	1.0	0.1 M D ₂ SO ₄	金丝	250	5	34	-0.091 ± 0.054
钛箔	0.038	1.0	0.1 M D ₂ SO ₄	金箔	1,000	5	3	-0.22 ± 0.12 ^y
(续)			0.1 M D ₂ SO ₄ +0.02 M PdCl ₂		1,000	5	4	-0.22 ± 0.12 ^y
钛棒	2.2	4.3	琼斯 ^o	金箔	100	4	3	-0.06 ± 0.15 ^y
(续)					500	6	2	-0.42 ± 0.21 ^y
钛颗粒 ^o	0.5		0.1 M D ₂ SO ₄	铂丝	250	7	22	0.00 ± 0.072
钛颗粒	0.5		0.1 M D ₂ SO ₄ +3 mM Na ₂ P ₂ O ₇	铂丝	250	7	66	0.044 ± 0.054
钛颗粒	40		0.1 M D ₂ SO ₄	铂丝	250	25	22	-0.009 ± 0.058
钛颗粒	40		0.1 M D ₂ SO ₄ +3 mM Na ₂ P ₂ O ₇	铂箔	250	25	22	-0.010 ± 0.060
钛颗粒	17		琼斯	金箔	500	26	24	0.021 ± 0.054
钛颗粒								
Ti-6Al-4V 合金	2.8	15.0	0.1 M D ₂ SO ₄	铂丝	670	5	87	-0.003 ± 0.031 ^t
Ti-6Al-4V 合金 ^p	2.7	14.3	0.1 M D ₂ SO ₄	铂丝	660	5	19	0.031 ± 0.044 ^x
TiFe 颗粒	1		0.1 M D ₂ SO ₄	钽箔	250	8	24	0.12 ± 0.06
CeAl ₂ 合金颗粒	11		0.1 M LiOD	钽箔	500	22	22	-0.051 ± 0.056
UPt ₃ 颗粒	57		0.1 M LiOD	钽箔	500	20	94	0.10 ± 0.06
(b) γ 射线发射速率								
阴极			电解液 ^z	阳极	电解细节			测得的5,488 keV 的γ 射线的产率 ^{aa} (γ射线/秒)
材料	质量(g)	表面积(cm ²)			电流(mA)	典型电压	时长(h)	
钽箔	0.58	7.5	0.1 M LiOH	钽箔	450	9	45	(-4.9 ± 7.4) × 10 ⁻³
钽箔	0.74	9.5	0.1 M LiOH	钽箔	510	9	164	-0.011 ± 0.004
钽片	7.7	12.9	0.1 M LiOH*	钽箔	200	4.6	50	-0.017 ± 0.012
钽棒	3.1	2.3	0.1 M LiOH	金箔	1,000	26	17	0.008 ± 0.011

(b) γ 射线发射速率								
阴极			电解液 ²	阳极	电解细节			测得的5,488 keV的 γ 射线的产率 ^{ad} (γ 射线/秒)
材料	质量(g)	表面积(cm ²)			电流(mA)	典型电压	时长(h)	
钛箔	0.089	2.0	琼斯*	金箔	320	5	42	-0.022 ± 0.011
钛箔	2.2	32	琼斯	金箔	1,000	4	12	-0.015 ± 0.034
钛箔	2.2	32	琼斯	金箔	1,000	4	6	0.012 ± 0.007
钛颗粒	25		琼斯	金箔	710	13	8	0.032 ± 0.036
钛颗粒	25		0.1 M H ₂ SO ₄	金箔	400	20	25	-0.019 ± 0.018
钛颗粒	25		0.1 M H ₂ SO ₄	金箔	765	16	16	0.017 ± 0.022
UPt ₃ 颗粒	42		0.1 M LiOH	铂箔	300	31	166	$(3.1 \pm 6.0) \times 10^{-3}$

a 弗莱施曼提供的电解池。使用之后分析了阴极的氢和氘——结果H/Pd为0.01、0.02，D/Pd为0.84、0.72。

b 阴极绕成一个紧密的螺旋状。初始阶段在大型中子探测器中进行监测，没有滑梭，持续了147小时，估算的检测限为1 ns⁻¹，之后的5小时检测限为0.2 ns⁻¹。再次使用之前阴极的表面用硫酸擦过。

c 300小时后用砂纸清洁阴极。

d 初始阶段阴极在大的中子探测器中进行监测，没有滑梭，在0.1M LiOD中进行了183小时；估算的检测限为1 ns⁻¹。使用之前用400目的金刚砂纸打磨。

e 管材来自托卡马克装置中的氘存储系统。

f 使用后分析了阴极中的氢和氘——结果：H/Pd为0.03，D/Pd为0.80。

g 上面实验中的电解液重复使用。

h 上面实验中的电解液和阴极重复使用；Na₂S以高浓度水溶液的形式加入。

i 使用前在1,000 °C真空下对箔进行了除气。使用后分析了氢和氘——结果：H/Pd为0.02，D/Pd为0.83。

j 使用之前将箔浸入Na₂S（浓溶液）中。使用后分析了氢和氘——结果：H/Pd为0.05，D/Pd为0.80。

k 将阴极切掉一半，使用后分析了氢和氘——结果：H/Pd为0.02、0.02，D/Pd为0.85、0.78。

l 熔体快淬带，由庄信万丰工程中心提供。

m 电弧熔化两次；在0.1 M LiOD溶液中电化学充氘一个月，然后在液氮中冷冻，浸入浓的Na₂S溶液并转移到中子计数电解池。

n 包括点焊在钨丝上的四个厚度为1~2mm、不同型号的圆形钨片（庄信万丰公司）以及受到应力的钨丝。

o 之前实验的电解液重复使用，使用钛阴极和铂阳极。

p 使用之前将材料加热到900 °C然后在水中淬火。

q 将琼斯使用的电解液中的AuCN用NaAuCl₄替代。

r 电流开启36小时，然后每小时在200 mA和20 mA之间变换一次。

s 电流开启36小时，然后每5分钟在300 mA和30 mA之间变换一次。

t 由于电解期间阳极的分解，电流在所示范围内缓慢变化。

u 电流开启36小时，然后关闭10小时、开启2小时并循环这一过程270小时。然后余下的时间中5,000秒为380 mA的阴极电流，4,000秒为10 mA的阳极电流。

v 电流每2小时开启或者关闭，依次循环。中子产率指的是“开启”期间的。

w 给定的误差（1 σ ，由整个实验期间计算而来）多少会有些变化，因为为了涵盖尽可能多的电解池的设置（主要是在规划的早期阶段），并不总是能够对地开展未通电 + 未通电和通电 + 未通电的实验，从而使得整个宇宙射线中子的探测效率存在少许差异，这是由于两个形式上相同

的电解池存在少许差异造成的。

x 采集这些数据时使用了一个不同的数据采集系统驱动滑梭和累计数据，旨在探寻猝发中子[10]。

y 电解池每过5分钟进行手动交换。

z 进行 γ 射线研究的所有电解液中 $\text{H}_2\text{O}:\text{D}_2\text{O}$ 都为50：50，标*的 $\text{H}_2\text{O}:\text{D}_2\text{O}$ 为41：59。

aa 当前测量中，用一系列标准的 γ 射线源和一个放射出6,129 keV γ 射线的 $^{238}\text{Pu}/^{13}\text{C}$ ($\alpha, n\gamma$) 源对系统进行了校准。放置各个电解池时它们的阴极应尽可能地靠近探测晶体，探测效率通过将之前测量^[21]的点效率函数对阴极体积进行积分计算出来。在预期的全能峰、单逃逸峰和双逃逸峰的位置（5,488 keV、4,977 keV和4,466 keV）处寻找峰，这些位置是用参考文献22中推荐的方法预测的。 英文

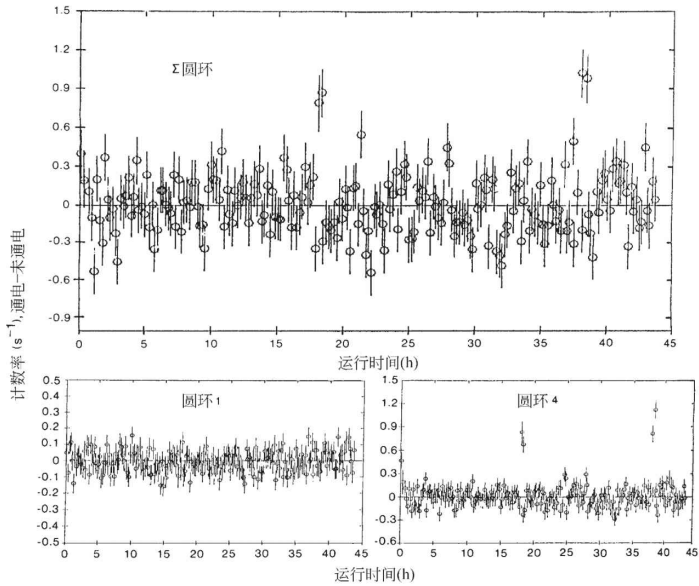


图3．从大型高效率中子探测器的一次典型实验中获取的数据。它们展示了通电和未通电的电解池计数率的差异，这是通过持续地变换滑梭位置实现的，具有0.1 M D_2SO_4 的电解池中含有40 g 钛颗粒。显示的误差为每5分钟计数区间的 1σ 误差。除了将探测器作为一个整体得到的结果之外，还显示了五个圆环中的两个获得的结果，组成圆环的 $^{10}\text{BF}_3$ 正比计数器直径为2 in，活性长度为107 cm。圆环2、3和5（未显示）的计数与圆环1的非常相似。只在圆环4中观察到了明显的猝发，因此这是一个假信号。一只管（内直径90 mm）穿过探测器的中心，屏蔽设备包括6 in 的硼酸树脂、1 mm 的镅和2 in 的铅。中子探测效率比较高，并且与中子能量无关，在0.5 MeV 中子（Am/Li）的48%到4.2 MeV中子（Am/Be）的40%之间变化。本底计数率为每秒4~5个计数，大部分中子来自宇宙射线。五个圆环计数器中的每一个都有自己独立的前置放大器、脉冲形状放大器和甄别器，计数的中子的平均能量通过最外侧的环形计数器（环5）的计数与最内侧的（环1）计数之比得到。因为中子计数分布于五个环上，也因为平均捕获时间为135微秒，从一个源中同时猝发的多个中子可以被分别计数（例如，就像 ^{252}Cf 源一样）。前置放大器、高压部件和绝缘体都被囊括在一个干燥的电屏蔽箱中，我们消除了运行于PDP-11/45型数据采集计算机上同轴电缆的接地回路和诱发的电磁捕获（“天线”）效应，这是通过使用隔离的高频脉冲转换器并将同轴电缆在铁氧体环上缠绕多次实现的。中子探测器和与之相连的电子器件被置于一个控温的空调房中，这个空调房有两英尺厚的混凝土墙壁和屋顶。 英文

电解池细节和测量结果列在表2中。如果在整个运行过程中中子持续发射，则从表2中推导出钷的中子发射的最低限 (2σ) 为 $1.5 \times 10^{-2} \text{ n}\cdot\text{s}^{-1}\cdot\text{g}^{-1}$ 或 $1.5 \times 10^{-2} \text{ n}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$ 。就钷而言，这个数值为 $3 \times 10^{-3} \text{ n}\cdot\text{s}^{-1}\cdot\text{g}^{-1}$ 或 $4 \times 10^{-3} \text{ n}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$ ，然而后面的限值太高了，因为它并不适用于所用颗粒表面积大而不确定的实验。如果我们假设发射至多持续了一个小时的时间，那么限值为，钷： $7 \times 10^{-2} \text{ n}\cdot\text{s}^{-1}\cdot\text{g}^{-1}$ 或 $4 \times 10^{-2} \text{ n}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$ ，钷： $8 \times 10^{-3} \text{ n}\cdot\text{s}^{-1}\cdot\text{g}^{-1}$ 或 $2 \times 10^{-2} \text{ n}\cdot\text{s}^{-1}\cdot\text{cm}^{-2}$ （比用小颗粒的实验小得多）。中子发射速率限值比参考文献1报告的约 10^4 s^{-1} 低数个数量级，比参考文献2报告的约 0.4 s^{-1} 低一个数量级。值得注意的是，我们研究的限值也可以在那些冷核聚变可能会增强的电解池中得到，尤其是使用钷阴极，以大质量（40 g）的多孔颗粒来提高反应体积和表面积，而且特意选择能够促使氘吸附到阴极的电解液^[13]（见图3）。正如后面讨论的，我们没有展示氘在金属晶格中数目的结果。 [英文](#)

由于表2给出的纯计数率是大得多的本底速率之间的差值，我们使用发射速率为 $0.09 \pm 0.01 \text{ n}\cdot\text{s}^{-1}$ 的校准过的²⁵²Cf源（每秒 0.024 ± 0.003 次裂变）和一个物理上一样的空白进行了实验。结果为 $0.14 \pm 0.05 \text{ n}\cdot\text{s}^{-1}$ ，其一致性令人满意。而且，由于²³⁸U的自发裂变，不通电的UPt₃电解池预期的中子输出为 0.22 s^{-1} 。与一个空电解池对比后测量值为 $0.20 \pm 0.06 \text{ s}^{-1}$ 。我们对滑梭差异这一结果的信心似乎得到了验证。在CeAl₂和UPt₃电解池中进行了测试，以期源自那些金属晶格的大的有效电子质量可以以某种方式模拟“重电子”对核聚变的增强效应，就像μ子将两个氘核束缚得非常接近时一样。将钷带实验电解池的电源开关每隔两个小时（约八倍于带中的特征扩散时间）转换一次，以增强非平衡效应的表现，结果（负结果）如图4所示。 [英文](#)

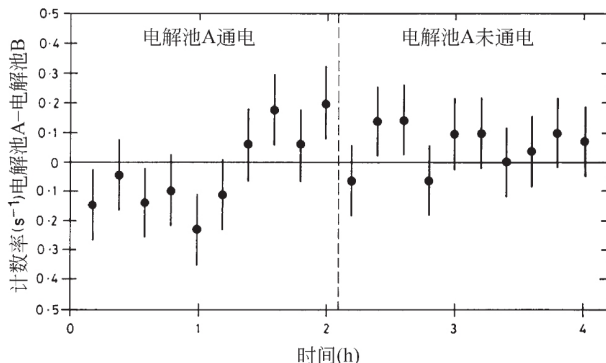


图4．电解池中子发射随时间的变化，使用熔体快淬的钯带状阴极和钯箔阳极，以两个小时为周期，轮换着打开电源使氘吸附、关上电源使之弛豫，这通过数据采集的计算机来实现：见表2的注脚^l。总的运行时长为110小时，“打开”和“关闭”数据的总和如图所示。运行90小时以后，我们向溶液中添加了1 μM 的 Pb^{2+} 离子（通过铅的沉积使表面中毒）。有或者没有 Pb^{2+} 离子的数据之间没有差异，所以将整个运行期间的数据都结合起来了。这次运行目的在于增强文中讨论的非平衡效应的表现。假设钯带具有高密度的晶界、位错和其他的晶格缺陷。因为“打开”和“关闭”的区间是钯带特征扩散时间的几倍，所以假设钯带的组成在完全充氘的条件（ $D/\text{Pd} \approx 0.83$ ）和（ $\alpha + \beta$ ）相区域的限制值（ $D/\text{Pd} \approx 0.65$ ）之间的 β 相区域循环。 [英文](#)

γ射线计数

由于已经表明质子-氘核冷核聚变预计进行的速率比氘核-氘核核聚变要快约8.5个数量级^[3]，我们通过寻找质子-氘核核聚变产生的 $D(p, \gamma)^3\text{He}$ 5,488 keV的 γ 射线对氢-同位素核聚变的电解增强进行了研究。我们使用了一个113 cm³的铅防护n型高纯锗晶体 γ 射线谱仪，在内有轻水和重水混合物的多种冷核聚变电解池中探寻一切能量范围在0.1~7 MeV的 γ 射线。结果也在表2中列出，它们一致表明没有 γ 射线放出。如果我们假设放射在整个运行过程中得以维持的话，那么由表2中可获得的 γ 放射值的最低限（ 2σ ），钯为 $7 \times 10^{-3} \gamma \cdot \text{s}^{-1} \cdot \text{g}^{-1}$ 或 $1 \times 10^{-3} \gamma \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$ ，钛为 $1.4 \times 10^{-3} \gamma \cdot \text{s}^{-1} \cdot \text{g}^{-1}$ 或 $4 \times 10^{-4} \gamma \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$ 。琼斯等人^[2]报道核聚变的活性仅可保持4~8小时，而且始于电解开始后约1小时，在这样的条件下 γ 射线放射速率的标准偏差典型值约为0.05 s⁻¹而 2σ 值对钛而言为 $4 \times 10^{-3} \gamma \cdot \text{s}^{-1} \cdot \text{g}^{-1}$ 或 $3 \times 10^{-3} \gamma \cdot \text{s}^{-1} \cdot \text{cm}^{-2}$ 。运行后对钯阴极的吸附物及所用的轻水和重水混合物电解液的氢同位素进行分析，给出了令人满意的氘和氢的比值，在1.5~2.5的范围内。我们注意到，如果假定的核聚变过程的增强对质子-氘核核聚变像对氘核-氘核核聚变一样有效的话，那么，因为在更轻的氘核-质子核系统中的隧道效应增强^[3]， γ 射线测量对冷核聚变过

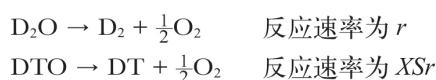
程实际能提供比中子测量更加严格的限值。由于金阳极上有金的溶解且在阴极上有相应的金的沉积，对从一些电解池获得的结果的解释变得较为复杂：这也影响了最初的工作^[2]。 [英文](#)

氙的富集

弗莱施曼等人^[1]宣称氙产生速率约为每秒 10^4 个原子，与他们报道的中子发射速率相等。他们使用了一种差分技术，这种技术是将铯阴极电解池中氙的累积与另一个铂阴极电解池中氙的累积进行比较。他们以规定的时间间隔取样分析，同时添加新的重水以保持总电解液体积不变。 [英文](#)

电解富集被广泛用于分析前增大水中氙的浓度^[14]。要实现可重复的结果需要仔细控制电解，因为富集因子变化很大（参考文献15、16；奥特莱，个人交流）：改变电极材料、电极表面状态（活性）、电流密度（过电压）和温度的改变都会造成巨大的影响。如果不加注意，富集因子的变化可以超过两倍^[16]。因此只有考虑这个已知的可变电解富集因素才能对弗莱施曼等人的宣称作出评估。令人惊异的是，弗莱施曼等人^[1]宣称他们的铂电解池中没有电解富集。 [英文](#)

如果氢同位素的电解过程速率表述如下



其中 r 代表电解反应速率， S 为氙-氙分配系数， X 为氙（T）在溶液中的摩尔分数，那么氙的累积可以表示为^[10]

$$\frac{X}{X_0} = \frac{1}{(S+\alpha+\gamma)} \left\{ 1 + \alpha + \gamma - (1-S) \exp \left[- \frac{(S+\alpha+\gamma)t}{N_0} \right] \right\} \quad (1)$$

其中通过添加新的重水（包含一定量摩尔分数为 X_0 的氙，与衰变速率成正比）保持溶液总体积不变，溶液取样速率与电解速率之比为 α ， γ 代表溶液蒸发的速率与电解速率之比——需要进行一个小的纠正，可以假设从电解池中溢出的电解气体在水蒸气中是饱和的。在目标时间尺度上， S 的变化可以给出富集情况的变化

$$\delta\left(\frac{X}{X_0}\right) = -\frac{rI}{N_0} \delta S \quad (2)$$

如果溶液被大气中吸附而来的氢污染了，那么如果 S_{obs} 代表由方程（1）推导的表观DT富集系数，则 $S_{\text{obs}} = S/[0.5(1+f)]$ ，其中 $f = (1-X_{\text{H}})/(1+X_{\text{H}}(S_{\text{HD}}-1))$ ， X_{H} 代表氢的摩尔分数， S_{HD} 代表HD的分配系数（HDO和 D_2O 反应的相对速率）。因此，除了一个电极到另一个电极的固有变化之外，很显然任何吸附氢的量变化都将会表现出表观富集系数的变化：

$$\frac{dS_{\text{obs}}}{dX_{\text{H}}} = \frac{S_{\text{HD}}}{2[1+X_{\text{H}}(S_{\text{HD}}-1)^2]}$$

我们发现除非采取非常严格的预防措施（而且我们相信我们采用的实验步骤与参考文献1中所用的是非常相似的（弗莱施曼，个人交流））， $X_{\text{H}} \approx 0.07$ 这样的值是常见的。在这些条件下， X_{H} 仅0.01的变化将会使 S_{obs} 变化0.02，鉴于所宣称的效应很小，这个变化是非常显著的。

英文

关于差分富集是否能够用来说明参考文献1的结果，任何这样的评价关键取决于 X_0 的值，这个值未曾被报告过。使用 r （ 1.24×10^{18} 原子/秒）和 N_0 （ 14.6×10^{23} 个原子）的值^[1]，我们从方程（2）计算出，如果 X_0 处于商用 D_2O 范围的极低端（3 Bq·ml⁻¹），需要 $\delta S = 0.46$ ；如果它属于中等（10~15 Bq·ml⁻¹），需要 $\delta S \approx 0.1$ ；如果它比较高（80 Bq·ml⁻¹）， $\delta S \approx 0.02$ 就足够了。 英文

方程（1）在铂和钯阴极上的适用性都经过了实验的验证，是同量热和中子计数实验联合进行的（见图5的图注），使用氚初始含量为13 kBq·ml⁻¹的 D_2O （效率经过了校正）。用这个方程拟合所有给出的实验数据（图5），对钯而言， $S_{\text{obs}} = 0.59$ ，对于铂， $S_{\text{obs}} = 0.61$ 。对氢吸附量做校正，采用 $S_{\text{HD}} = 6$ （参考文献16），得出 $S \approx 0.48$ ，与之前的工作和理论预期一致（ $S = 0.46 \pm 0.02$ ，（参考文献14、15；罗森和奥特莱，个人交流））。对于单独的电极，钯的 S_{obs} 在0.46到0.65之间变化（校正后在0.42到0.58之间），而铂的 S_{obs} 在0.56到0.85之间变化（校正后在0.43到0.69之间）——对于单独电极的总范围 $\delta S_{\text{obs}} = 0.4$ ，这是

以对弗莱施曼等人的结果^[1]给予解释。

英文

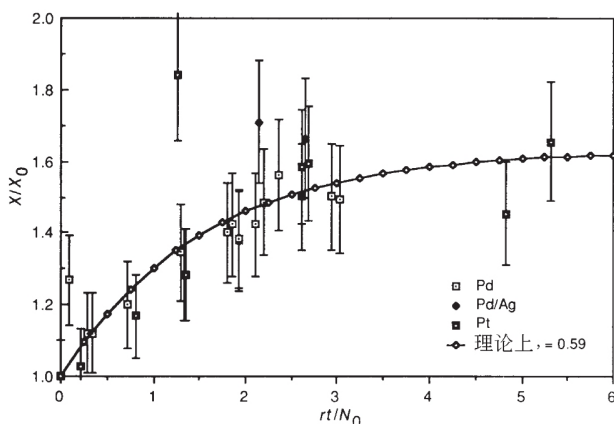


图5．一定体积的开放电解池中氘的电解富集，使用钯和铂阳极：相对计数率 X/X_0 相对于电解量 rt/N_0 的关系（符号在文中进行了定义）。初始的计数率（经过了效率校正）为 13.0 ± 0.6 $\text{kBq}\cdot\text{ml}^{-1}$ 。误差为 1σ 。钯电解池是FPH量热计，490~660小时后取样，表2中第一部分的电解池（脚注a~e）在运行结束的时候取样，一个电解池通过高效中子探测器取样——表2的脚注k。曲线是对方程（1）的拟合。

英文

从这些结果和讨论中可以很清楚地看到，要证明所报告的氘的累积^[1]是发生核聚变的可靠的实验证据，还需要更多的证据。

英文

材料表征

使用125 μm 厚的钯箔，在0.1 M的LiOH溶液中以钯为阳极、电流密度为100 $\text{mA}\cdot\text{cm}^{-2}$ 的条件下，充氘率（通过冷冻在液氮中样品的热萃取质谱和独立的电化学萃取获得^[10]）达到 $\text{H}/\text{Pd} = 0.95 \pm 0.05$ 约耗时1小时。在0.1 M LiOD中充氘率的上限更低（ 0.84 ± 0.03 ）。在中子计数和量热实验中极化时间更长的钯棒（直径1 mm和2 mm）显示 $\text{D}/\text{Pd} = 0.76 \pm 0.06$ 。对于给定的充氘率，其平衡压力要高于同样充氢率的平衡压力，这是众所周知的^[17]。用中断电流的方法确定了所得到的过电压在0.8~1 V的范围内（参考文献1）。 D_2O 从初始的99.9%，24小时内降为约98.5%，继续电解数个星期降为88%~98%（通过红外光谱进行分析）。导致钯中H/D的比值变为0.02~0.04。

英文

电解期间，所有的钯阴极都会覆盖上一层从暗无光泽到致密黑色这样外观不同的物质。在后面的实例中，也发现过疏松的黑色物质，在一

些极端的情况下它会在电解进行期间掉落，结果导致阴极的严重腐蚀。该层本身清楚反映了阴极表面形态的改变。在高电流密度、高温、较小直径的棒上以及在长期频繁的阶跃式改变电流密度的条件下，容易生成厚的黑色层。该层在螺旋状阴极的外侧要比内侧更容易观察到，而且在D₂O中极化过的阴极上也比在H₂O中极化过的阴极上更容易观察到（这可能与相同含量情况下Pd-D体系有更高的平衡气压有关），而且在不同来源的材料上其外观也不相同。这一发现可以用已有的理论^[17]给予解释：由于充氢率很高，钯中将出现微裂缝和裂缝以释放掉由此而来的机械应力，同时也有假说认为这种效应依赖于金属表面的应力状态和它的微结构。

[英文](#)

在LiOD中使用的阴极表面层含有锂，通过二次离子质谱（SIMS）分析表明锂的浓度分布已经深入金属内1 μm。SIMS图像显示锂并不是规则分布的，而是看起来像被捕获在表面层中的微裂缝里。

[英文](#)

表面分析表明有一定数目的其他元素位于表面层之上或者其中，有极少量的铂，痕量的铜、锌、铁、铅和硅：铂可能来源于阳极，而硅来自玻璃容器。毫无疑问，主要的其他污染物应该来自溶液：我们发现的量级（按原子数计算是百分之几，限于表面层）与在浓度为10⁻⁹~10⁻¹⁰ M的溶液中长时间电解后的沉积物是一致的。可能有人批评，低水平的沉积物会使潜在的催化活性中毒：因此我们在一些实验中使用了电解预处理，以期减少表面的污染物。我们通过在同一溶液中重复实验，简单地改变阴极，或者事先将溶液在一个分开的电解池中进行处理。

[英文](#)

因为有报告声称有一种非同寻常的机制导致核反应进行过程中优先生成非辐射性的⁴He，我们用真空熔融/质谱仪对四个阴极（表2中的前4组）进行了分析。由于钯在熔点处的高蒸汽压导致实验发生困难，所以内部标样是用离子注入法向阴极上切下的样品注入10¹³和10¹⁵个⁴He原子而得到的。这种确定³He和⁴He的方法的检测限约为每份样品8×10¹⁰个原子，即每克（1~10）×10¹¹个原子。我们没有发现³He和⁴He。如果核聚变以参考文献1中所报告的速率发生，预期的测量值应约为每克10¹⁶个原子。

[英文](#)

众所周知^[13]，氢在钛阴极上析出得到的是一个致密的网状氢化物沉淀，该氢化物可以采用标准的金相学方法进行观察，它会渗入到表面以下。在0.1 MD₂SO₄电解液中，100 mA·cm⁻²的电流密度下，网状物1小时渗入约30 μm。贵金属的沉积会阻止电解液的吸附，这可能是通过降低过电压和促进气体产生造成的。琼斯等人^[2]采用的在“啤酒”（译者注：此处有调侃琼斯等人使用的多种盐混合物溶液的意思）中电解得到的氢化物沉淀局限于颗粒边界；其他实验表明电解液中PdCl₂的存在会导致这一效应，可能是钯在阴极电镀的结果。很清楚的是，假设含有化合物TiD₂阴极的核聚变速率表达式完全是误导人的：金相学表明成对氘的数目非常少，因此，所声称的每个氘对的核聚变速率远高于给出的数值，所以相比之前的解释^[2]，这一结果更难与预期的相符。 [英文](#)

讨论

对冷核聚变的兴趣催生了大量中子计数实验。众所周知，通常情况下，由于不可预期的系统变化，在不同的时间和位置对信号+本底和本底的计数测量（如参考文献1所为）是不可取的。对于低计数率实验尤为如此。对本底速率变化的补偿和选定过程的误差评估都很成问题。琼斯等人的工作^[2]存在这些错误^[18]，是应该被批评的。在参考文献2中需要注意的是，十四次实验只有一次显示出明显的效应，而且仅仅是因为给这一次特殊的实验赋予了比其他实验小的计数误差。这篇文章中我们试图用滑梭的办法来减小本底和计数器的变化以及误差计算的不确定性。对一些更加惊人的声称进行思考时，我们注意到，因为人所共知的¹⁰Bf₃和³He正比计数器对湿度的敏感性，以及计数器放大器系统对接地回路的敏感性，因此更加的谨慎是明智的。在我们的研究中，中子计数器被分成几部分，而且从不同部分得来的信号之间的关系是已知的，所以不同部分给出不一致的信号而产生的假信息是可以分辨出来的。

[英文](#)

重现这些效应之所以失败，是由于严格除氢的需要造成的，已经有结论指出钯电极在使用前必须经过铸造并小心地除气，以除去所有痕量的碳和杂质氢（译者注：氢在此被看作杂质是相对于氘而言），它们可能存在于位错点或者其他的一些高能位点上（参考文献19；哈金斯在1989年5月圣菲举行的冷核聚变专题讨论会上的报告）：然而这与该效

应“核聚变”起源的假定不符，因为在低能量范围，质子-氘核核聚变明显快于氘核-氘核核聚变^[3]。而且，最初的报告^[1,2]除了小心盖好电解池以外，并没有指出任何特殊预防措施以排除空气中的水蒸气。我们沿用类似的步骤，发现重水与空气中的水汽交换而退化的现象迅速发生。另外，有人指出在相当的一段时期内维持一个高的电流密度是必需的（见阿普尔比在1989年5月圣菲举行的冷核聚变专题研讨会上的报告），尽管我们并不完全清楚后面的这个结论是对参考文献1所报道现象的重现还是有所不同。在我们的中子计数实验中，新形成的位错是通过塑性形变产生的，一些计数实验是在高达 $1 \text{ A}\cdot\text{cm}^{-2}$ 的电流密度下进行的（表2），在使用等温量热计的一个实验中，其高电流密度保持了相当长的一段时间（表1）。痕量的铂在阴极上沉积，假设这会导致氘析出的过电压降低，从而降低阴极中氘可达到的浓度水平，也被认为是对不可重复性的一种解释（弗莱施曼，个人交流）。当我们在我们的中子计数实验中使用铱阳极时，并没有观测到任何效应。 [英文](#)

充氢和充氘的时间与预期的扩散时间一致（ x^2/D ，其中扩散系数 $D = 10^{-7} \text{ cm}^2\cdot\text{s}^{-1}$ ， x 为样品的半径或其厚度的一半）^[10]，并且核计数和量热实验进行的时间也总是远大于这一时间尺度。此外，在铱的电解充氘（氢）过程中，显然会有一个浓度梯度，一个移动的相边界，并且金属外表面的原子层会被氘所饱和^[17]（也可能过饱和）。因此，可以预期，足够灵敏的设备可以在这种材料完全充氘以前检测到核聚变过程。因为我们的中子探测实验的灵敏度是弗莱施曼等人^[1]的约 $10^5 \sim 10^6$ 倍，看上去似乎不太可能发生任何伴随着铱充氘的大大增强的核聚变并产生中子发射。当然，我们注意到总是有可能构建一个实质上尚难检验的理论，该理论涉及金属或其表面假定的特殊情况。因此，仔细表征具有正结果的材料是非常重要的。 [英文](#)

氘核-氘核反应的中子分支会被完全抑制掉而代之以（ $t+p$ ）分支，这一观点已得到一些论证，进一步的论证指出（庞斯，个人交流）在电极内部作为核过程产物的氘并不一定与电解液发生交换，因而也就可能检测不到。然而，这样一个核过程的其他的产物——高能质子在它与晶格相互作用的时候应该能被检测到，产物中还应包括中子发射：我们估计，已知质子损失能量的速率，通过与相邻元素（ p, n ）反应截面的比

较，产率约为每质子 10^{-6} 个中子，如果核聚变以参考文献1中所报道的速率完全通过(t+p)分支进行的话，我们的计数实验可以产生的中子产率为 10^4 s^{-1} 。 英文

由于在PdD和TiD₂中都存在相对较大的氘核-氘核间距，可能有争论说核聚变需要一些晶格中的非平衡状态——也许在钯的 α/β 相边界，或者在生长中的TiD₂针状物的尖端，又或者在一个晶格缺陷上，在这些地方，也许氘核-氘核或者质子-氘核的间距会大大减小。本文中，我们通过脉冲电流创造了一个非平衡的状态，但是仍没有检测到中子发射（图4）。 英文

一些对产生表观“过热”现象的解释强调的是在具有催化性的金属表面的复合^[20]：然而除了偶尔的突然爆发，它不会导致任何可观测的中子发射，通过比较为了维持电解池的体积而加入的水的体积与通过电解池的电荷数量，我们发现，这并不是一个重要的效应（与其他研究者的结论一致^[9]）。在液体上方的气体空间复合，不是发生在暴露的阴极表面，就是被从阴极上腐蚀下来的胶体金属颗粒所催化，但是，这仅能解释最近报道的所观察到放热实验中的一些现象（见弗莱施曼和庞斯在1989年5月于洛杉矶举行的电化学会议上的报告）。在讨论参考文献1的结论时，我们倾向于关注“简易的”弗莱施曼、庞斯和霍金斯（FPH）量热计的特征，因为我们只观测到了一些小的效应（在固有的不确定性的水平上），在一种标定很困难的量热计（FPH型）上，这些效应可能被错误地认为是来源于冷核聚变。使用同样的电极和电解液材料并利用没有这些问题的量热计，发现这样的电解池并未显示出这些效应。 英文

有两点关于标定的问题可能对于FPH型量热计所获得的表观结果产生重大的影响：首先是标定何时进行，其次是标定如何进行。关于第一点，从我们和刘易斯等人^[8]的工作来看，似乎在电解进行的前10,000分钟进行的标定是非常错误的，这将会导致错误的结论，即把处在平衡态的电解池误认作处在放热状态。关于第二点，弗莱施曼等人^[1]对使用内部的电阻加热器、通过测量牛顿冷却定律的损失来进行标定的方法进行了描述。通常情况下，这一过程包括了在电解出现时给加热器施加功率，紧接着跟踪温度-时间轨迹，直到达到稳定状态，然后把加热器关

掉，记录冷却曲线。这个过程可以算出工作温度下一个电解池的微分量热计常数的估计值， $k_d = d(\Delta P) / d(\Delta T)$ （其中 P 为功率， T 为温度），有两方面的因素会造成这个值的误差变大。首先，因为任何的标定程序都需要5~10小时，要得到参考液面处的正确数值，需要进行外推：这估计会对结果造成20%或更大的误差。此外，因为电解池的蒸发量会随着温度的升高而明显增大，随着温度的升高，基线斜率也会增大，这种错误所产生的效应相应的会更加明显：声称的效应实际上在电解池以最高的输入功率运行时是最大的。第二，这种量热计是非线性的（方程（3），图2的图注），当温度梯度较大时，非线性效应比较明显：它们不能用简单的牛顿冷却定律来描述。如果一个微分量热计常数通过输入功率来导出，计算出的输出功率应该为（来自图2的图注中的，方程（3））

$$P_{app} = k_d \Delta T = (k_{sb,0} + k_c) \Delta T + 3(k_{sb,0}/T_0) (\Delta T)^2$$

与正确的输出功率（方程（3））进行比较，则有

$$P_{app} - P = 3k_{sb,0}(\Delta T)^2/2T_0$$

如果与电解功率相比，施加在加热器上的功率很大，那么这个误差会更大。从参考文献1给出的数据进行反演计算表明，声称的效应在焦耳输入功率为6 W的数量级时最大。对我们的FPH型量热计而言，这将得出 $\Delta T \approx 50 \sim 60$ °C。因此，如果这些电解池经过这种方法进行标定，将能观察到0.8~1 W量级的表观过热。我们的标定方法（见图1的图注）显著地减小了这种来源的误差。最原始的报告^[1]实质上很明显是初步的，而且从上面的证据来看，在没有详细描述所采用的实验步骤和用于抵消使用一个简单量热计带来的系统误差的方法之前，最初的报告^[1]中的宣称是难以评估的。 [英文](#)

在仔细控制、很好理解实验条件并使用完备表征材料的条件下，我们认为我们的工作为电解池中尚未观察到冷核聚变建立了清晰的界限。更进一步的细节参见参考文献10。现在对观察到冷核聚变的声明应该符合类似的数据分析和材料表征标准，这样才能对其作出适当的评估。

[英文](#)

(李琦 翻译；李兴中 审稿)

Limits on the Emission of Neutrons, γ -rays, Electrons and Protons from Pons/Fleischmann Electrolytic Cells

M. H. Salamon *et al.*

Of the many experiments conducted worldwide to investigate the claim of Martin Fleischmann and Stanley Pons to have carried out nuclear fusion by benchtop electrolysis in 1989, those reported here provided some of the most compelling contrary results. Michael Salamon was a physicist at the same university (Utah) as Pons, and he obtained Pons' agreement to re-run the experiments using the same apparatus. After exhaustive trials, Salamon's team found no evidence of "cold fusion". Pons' claim that excess heat had been generated in one event after a power failure had prevented the computer from collecting data only added to the growing scepticism and suspicion about the original claim. At one point, these experiments provoked threats of legal action against Salamon. [中文](#)

Emissions of γ -rays from the cold-fusion cells used by Pons and Fleischmann were monitored in Pons' laboratory at the University of Utah by NaI detectors nearly continuously over a five-week period. No evidence of fusion activity was observed above power limits varying between 10^{-12} and 10^{-6} W for the known fusion reactions.

In addition, neutron-track detectors indicated an integrated upper limit of approximately 1 emitted neutron per second from any of the cold-fusion cells over a period of 67 hours. [中文](#)

PONS and Fleischmann¹ claim to have achieved “cold fusion” of deuterium nuclei in electrolytic cells containing palladium cathodes and D₂O (with 0.1 M LiOD) electrolyte, which produced excess heat of the order of a few watts. Their claim was based on the lack of a known electrochemical mechanism for the observed heat excess and the emission of γ -rays and neutrons at levels slightly above background. These latter data have been criticized²⁻⁴, but reports of tritium production in similar cells⁵ and the discrepancy between cell power inputs and outputs in several laboratories⁶ have sustained the controversy despite a large number of negative results⁴. [中文](#)

The known $d + d$ and $d + p$ reactions and their energy yields (Q) are⁷: $d(d, p)t$ ($Q = 4.03$ MeV); $d(d, n)^3\text{He}$ ($Q = 3.27$ MeV); $d(d, \gamma)^4\text{He}$ ($Q = 23.85$ MeV); $d(d, e^-)^4\text{He}$ (internal conversion) ($Q = 23.85$ MeV); $d(p, \gamma)^3\text{He}$ ($Q = 5.49$ MeV). [中文](#)

Several weeks after his initial press announcement, Pons allowed us into his laboratory to make independent measurements of any radiation emanating from his operating electrolytic cells. Using equipment that was immediately available, a lead-shielded sodium iodide (NaI) detector (8×4 in.) was installed below his cells (Fig. 1) and collected data nearly continuously for over five weeks in a γ -ray energy range of 0.1–25.5 MeV. In addition, several neutron detectors, which integrated the neutron flux over a period of approximately three days, were placed within the water tank adjacent to the cells; these were made of ²³⁵U foils sandwiched between nuclear-track-detecting plastic film. [中文](#)

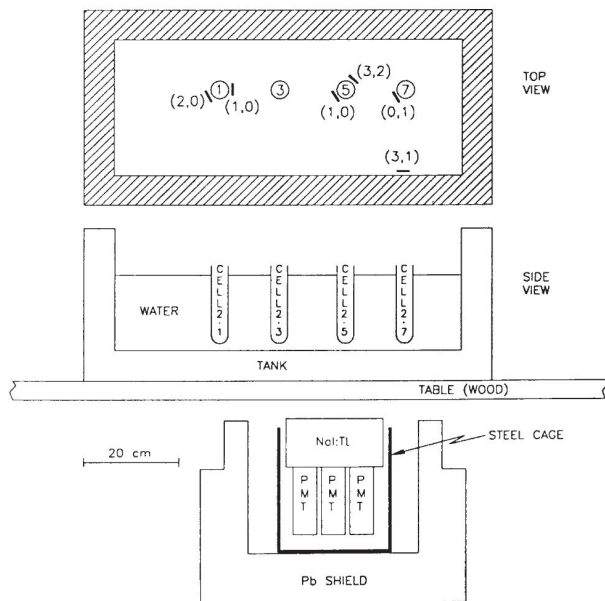


Fig. 1. Side view of the geometry of the electrolytic cells and NaI detector, and top view of the cells with neutron-detecting sandwiches in place (thickline segments). Cells 2-1, 2-5 and 2-7 have palladium cathodes with diameters/lengths (in cm) respectively of 0.4/1.25, 0.4/10.0 and 0.1/10.0; cell 2-3 has a platinum cathode of dimensions 0.1/10.0. The two numbers (n , m) shown for each sandwich in the top view are the number of fission fragments counted in the plastic film adjacent to the uranium foil (without, with) Cd covers. Only one plastic film per foil was analysed. [中文](#)

NaI Detection of γ -rays

Four open cells (no gas collection) underwent electrolysis nearly continuously while the NaI detector was collecting data (9 May to 16 June). These cells consisted of D_2O (0.1 M LiOD) electrolyte with platinum anodes; the cathodes were as described in Fig. 1. The cells were run in constant-current mode, and current settings were varied over the five-week interval. [中文](#)

The NaI detector system was placed under the table supporting the water tank and cells, so as not to interfere with other research activities in Pons' laboratory. Any γ -rays produced in the cells would thus pass through water, water tank and table before being detected by the 8×4 in. NaI detector. The energy-dependent, absolute

efficiency for γ -ray detection in the photo-peak (corresponding to complete γ -ray energy conversion within the scintillator) was determined with standard γ -ray sources in a separate laboratory, where an identical configuration of water, tank, table and detector could be installed or removed at will. Radiation limits given below are based on the absolute efficiency for a source at the location of cell 2-1.

中文

Spectral data accumulated by a pulse-height analyser were downloaded to a microcomputer every 0.5 or 1 h (live time) continuously over the five-week observation period, thereby minimizing the effect of integrated background on transient signals. The system's gain was set so that γ -rays in the energy interval 0.1–25.5 MeV were recorded. An aggregate spectrum corresponding to 785 h of operation is shown in Fig. 2*a, b*. 中文

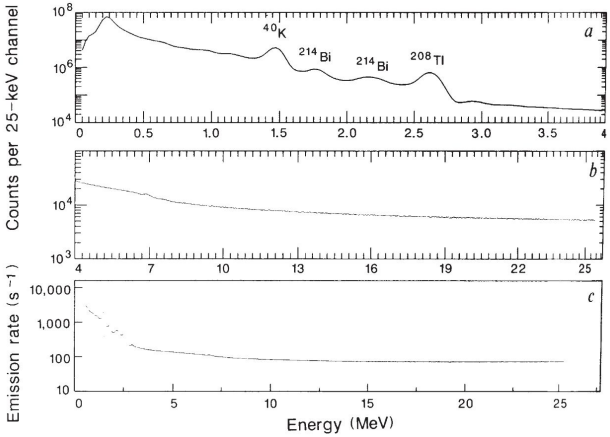


Fig. 2. *a, b*, Aggregate γ -ray spectrum for 785 h of live collection time. The dominant background lines are ^{40}K (1.4608 MeV), ^{214}Bi (1.7645 MeV), ^{208}Tl (2.6146 MeV), a backscatter peak at ~ 0.23 MeV, and a broad peak at ~ 2.17 MeV due to two lines, ^{214}Bi (2.1186, 2.2042 MeV). The detector energy resolution is given by $R = 0.07E^{-1/2}(1 + 1.3/E)^{1/2}$, with E in MeV, where the leading factor is the detector's optimal resolution and the additional factor is caused by the presence of noise at the charge-integrating input of the pulse-height analyser's analog-to-digital converter. The integral nonlinearity of the system electronics was found to be $<0.1\%$ over the interval 0.1–3.5 MeV, and 0.2% over the full interval 0.1–25.5 MeV. System gain variations (owing to phototube drift, for example) were monitored and found to be $<3.5\%$ over the full five-week interval and $<0.5\%$ over any 24-h interval; *c*, γ -ray source emission-rate limit against energy for the general γ -ray search over

the range 0.1–25.5 MeV (see text). The probability of falsely rejecting a signal at these limits is $<10^{-3}$. [中文](#)

Individual spectra (1,116), each of 0.5 or 1.0 h live integration time (for a total of 831.0 h of live time), were searched for transient γ -ray signals above background. Background for each individual spectrum was obtained by averaging several (10–50) successive spectra to form an aggregate spectrum, which was then subtracted from the original spectrum to form a “residual spectrum”. This was performed for each individual spectrum, yielding 1,116 residual spectra. Any transient anomalous signals of duration <10 –50 h would then appear in the residual spectra as positive excesses amidst Poisson fluctuations about zero. Signals of longer duration were searched for with even greater sensitivity by performing a similar operation on the collection of aggregate spectra. [中文](#)

To correct for temporal variations in the detector system’s gain and pedestal (the pulse-height-analyser channel corresponding to zero energy), the gain and pedestal were determined for each individual spectrum by fitting to the background γ -ray lines. All spectra were then rescaled to a common gain with zero offset before background subtraction, thus minimizing artefacts in the residual spectra arising from gain or zero shifts, or both. [中文](#)

Neutron flux limits: $d(d, n)^3\text{He}$. Neutrons from the $d(d, n)^3\text{He}$ fusion channel have an initial kinetic energy of 2.45 MeV and a mean free path in water of 4.9 cm, which decreases to ~ 0.4 cm as the neutron thermalizes. Because each cell is surrounded by several inches of water, most neutrons emitted would thermalize in the surrounding water bath and generate a 2.22-MeV γ -ray from the $n(p, d)\gamma$ reaction; Monte Carlo calculations show for a point source of 2.45-MeV neutrons located at cell 2-1 that 62% of the emitted neutrons would be captured by hydrogen in the water bath. The absolute photopeak detection efficiency (for cell 2-1), measured with a Am-Be neutron

source, was found to be 3.0×10^{-3} . 中文

The presence of a γ -ray signal above background at 2.2 MeV was sought in each residual spectrum by fitting a gaussian (of central energy 2.2 MeV and variance determined by detector resolution) to the residual spectrum in the energy interval 2.0–2.4 MeV. The frequency distribution of the fitted amplitudes, in units of pW of fusion power, is shown in Fig. 3a. Of these 1,114 spectra, the maximum fitted amplitude is 10 pW. In this distribution (and others following) we have excluded two spectra that contained photopeaks due to ^{22}Na and ^{137}Cs sources brought into the laboratory by other personnel. 中文

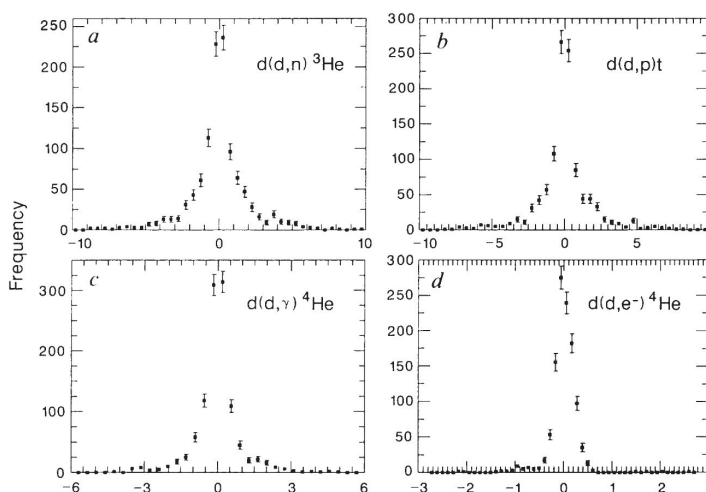


Fig. 3. Estimated rates for the four $d + d$ fusion reactions. For each of the 1,114 γ -ray spectra obtained from data-collection episodes lasting 0.5–1 h, a residual spectrum was obtained by subtracting an averaged background spectrum from the signal. A fit was then made to each residual by scaling the expected form of the γ -ray spectrum for each reaction; the fit yields a magnitude that can be positive or negative. The figures here are histograms of those 1,114 magnitudes. In a and b, the rate is expressed in units of fusion power (a: pW; b: mW); for c and d, reaction rates are used (c: s^{-1} ; d: 10^3 s^{-1}). In each case the histogram is approximately a gaussian distribution of amplitudes centred around zero, indicating no measurable rates for any of the fusion reactions. 中文

Proton flux limits: $d(d, p)t$. The fusion channel $d(d, p)t$ ($Q = 4.03$ MeV) has been a leading candidate for the cold-fusion process, both because of reports of excess tritium production⁵ and because its

reaction products come to rest within the palladium electrode (the range of a 3-MeV proton in palladium is $\sim 30\mu\text{m}$; ref. 8), thereby presumably avoiding the paradox of watts of fusion power being generated without observed particle emissions. In fact, a strong and distinct γ -ray signature exists for this reaction: the 3.02-MeV protons cause Coulomb excitation of the even-even isotopes of Pd, whose radiative de-excitations, between 0.37 and 0.56 MeV, are detectable by the NaI detector with efficiencies η given in Table 1. This table, adapted from ref. 9, lists for each Pd isotope its E2 (electric quadrupole) γ -ray energy and thick-target radiation yield (excitations per microcoulomb of protons) for 100% isotopically enriched samples, along with photopeak detection efficiency assuming cell 2-1 as the source, plus a factor accounting for absorption of the E2 γ -ray within the Pd cathode. Figure 4 shows a NaI γ -ray spectrum from a 3-mm target of natural Pd exposed to a beam of 3.02-MeV protons from a Van de Graaf accelerator (W. Schier, personal communication). Peaks at 0.37, 0.43 and 0.51 MeV are observed with their expected strengths.

中文

Table 1. Radiation yields of 3-MeV protons in palladium electrodes

Isotope (E2 energy) (MeV)	Isotopic fraction	Proton energy (MeV)	Excitation/ μC	NaI detector efficiency η	Pd escape probability
$^{104}\text{Pd}(0.555)$	11.0	3.30	$5.08(0.16)\times 10^5$	2.3×10^{-3}	0.81
		2.40	$4.35(0.17)\times 10^4$		
$^{106}\text{Pd}(0.513)$	27.3	3.30	$7.47(0.18)\times 10^5$	2.3×10^{-3}	0.80
		3.00	$4.00(0.12)\times 10^5$		
		2.70	$1.98(0.06)\times 10^5$		
$^{108}\text{Pd}(0.433)$	26.7	3.30	$1.19(0.03)\times 10^6$	2.2×10^{-3}	0.77
		3.00	$7.02(0.19)\times 10^5$		
		2.70	$3.76(0.08)\times 10^5$		
$^{110}\text{Pd}(0.374)$	11.8	3.30	$1.82(0.04)\times 10^6$	2.1×10^{-3}	0.73
		3.00	$1.11(0.02)\times 10^6$		
		2.70	$6.15(0.13)\times 10^5$		

中文

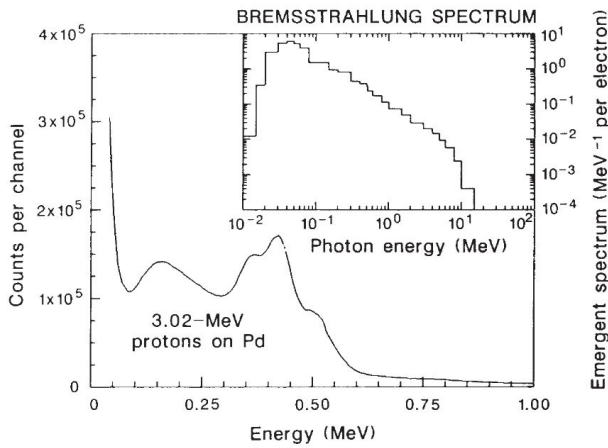


Fig. 4. Electric-quadrupole (E2) γ -ray lines from the isotopes of Pd, excited by 3.02-MeV protons, as measured by a 3×3 in. NaI detector. Three lines at 0.37, 0.43 and 0.51 MeV constitute a clear γ -ray signature for the reaction $d(d, p)t$ (a fourth line at 0.56 MeV from ^{104}Pd is too weak to be seen here). Their collective backscatter peak is at ~ 0.16 MeV. Inset: The emergent bremsstrahlung spectrum for an electron emitted at 20 MeV at the centre of a cylinder of H_2O , of height 36 cm and diameter 36 cm. The normalization is for a single electron, with the γ -ray flux integrated over the cylinder surface; the area under the spectrum corresponds to 1.1 photons per electron, including a small δ -function contribution of 0.511-MeV annihilation quanta not shown in the figure. This spectrum was obtained using the Monte Carlo code ETRAN¹⁵, which treats the coupled electron-photon transport using a recently developed set of bremsstrahlung cross-sections¹⁶. 中文

Convolving these line strengths with the resolution of the NaI detector, and using the efficiency factors from Table 1, a theoretically generated spectrum was scaled to optimally fit the 0.362–0.613-MeV region of each residual spectrum. The frequency distribution of the 1,114 fitted scaling factors (in units of mW of fusion power) is shown in Fig. 3b. None of the scaling factors exceeds 10 mW. This limit is comparable to the sensitivity of the calorimetric measurements made on these cells. 中文

More stringent limits can be placed on this channel by recognizing that the tritium, emitted with kinetic energy of 1.0 MeV, can initiate the $t(d, n)^4\text{He}$ reaction. By integrating the energy-dependent reaction cross-section¹⁰ over the range of the tritium within the Pd, we obtain a $d + t$ fusion probability of 4×10^{-5} per emitted tritium, assuming a

1:1 d:Pd ratio in the lattice. (We note that the probability p that a 1.0-MeV triton will produce a neutron within a deuterated palladium lattice via the reaction $t(d, n)^4\text{He}$ can be expressed as a function of r , the deuterium-to-palladium ratio (by number): $p = a_0 + a_1 r + a_2 r^2$, where $a_0 = 9.63 \times 10^{-8}$, $a_1 = 4.48 \times 10^{-5}$ and $a_2 = -5.40 \times 10^{-6}$. This expression, based on nuclear cross-sections from ref. 10 and hydrogen stopping power from ref. 17, is accurate to $\lesssim 10\%$ and is valid for $0.4 \leq r \leq 1.5$.) Monte Carlo calculations show that 39% of the resulting ~ 14 -MeV (centre-of-mass) neutrons will thermalize and be captured by protons within the water tank, yielding a 2.2-MeV γ -ray signal. From the absence of this signal, we obtain an upper limit of the fusion power amplitude of $0.4 \mu\text{W}$. [中文](#)

γ -ray flux limits: $d(d, \gamma)^4\text{He}$, $d(p, \gamma)^3\text{He}$, monoenergetic γ . A search was performed for 23.85-MeV γ -ray from $d(d, \gamma)^4\text{He}$ by fitting the expected line profile of a 23.85-MeV γ -ray to the residual spectra over the energy interval 23.6–24.1 MeV. Figure 3c shows the resulting distribution of fitted source emission rates; the maximum fitted rate is 5 s^{-1} , corresponding to a fusion power of 20 pW. A similar search was performed for 5.49-MeV γ -rays from $d(p, \gamma)^3\text{He}$; the maximum fitted source emission rate of 10 s^{-1} corresponds to a fusion power of ~ 10 pW. [中文](#)

A general search was also performed throughout the entire 0.1–25.5-MeV energy interval for possible γ -ray lines above background in each residual spectrum. Candidates were required to have at least one channel with counts in excess of 3σ (σ being the propagated Poisson error for that channel's count) and a summed excess of 9σ in the adjacent channels spanning the full width at half maximum of a γ -ray peak at the sampled energy. The only candidates found were due to imperfect rescaling of the spectrum's gain and zero relative to averaged background; these were identified by the presence of adjacent positive and negative excursions of equal magnitude, with a

zero-crossing at a known background peak position. No other candidate γ -ray lines were found. Allowing for detector efficiency, this yields the relationship between γ -ray emission-rate limit and energy (for cell 2-1) shown in Fig. 2c. [中文](#)

Internal-conversion electron flux limits: $d(d, e^-)^4\text{He}$. Even though nuclear de-excitation by internal conversion is greatly suppressed relative to radiative de-excitation for low-atomic-mass nuclei and for photon energies much greater than the electron mass, it has been suggested that cold fusion may in fact be occurring via internal conversion¹¹, which would produce an electron that carries off 23.8 MeV in kinetic energy. [中文](#)

Figure 4 shows the calculated bremsstrahlung spectrum emerging from a point-isotropic source of 20-MeV electrons located at the centre of a cylinder of water 36 cm in diameter (~ 4 MeV are assumed to have been lost within the Pd cathode¹²). The spectrum, normalized to one source electron, has an integrated area of 1.1 photons per electron. This bremsstrahlung spectrum, modified by detector efficiency, was scaled to obtain an optimal fit to each residual spectrum, giving a best-fit number of bremsstrahlung photons for each spectrum. Figure 3d shows the frequency distribution of the electron emission rate corresponding to the fitted bremsstrahlung photon number. The maximum fitted electron emission rate, 2.6×10^3 electrons per second, corresponds to a fusion power level of 10 nW.

[中文](#)

Neutron Detection with Nuclear Track Detectors

A significantly lower limit than the 10 pW discussed above on the mean neutron production rate during a 67-h interval (16–19 May) was obtained with neutron-detecting sandwiches made of ^{235}U -enriched (80%) uranium foils and nuclear-track-detecting plastic, Lexan polycarbonate. Six sandwiches were installed in the water tank

containing the cells (Fig. 1); each consisted of two uranium foils, each with an area of 1.4 cm^2 and mass $\sim 0.078 \text{ g}$, held between two pieces of 0.01-in.-thick Lexan polycarbonate. One of the two foils was shielded against slow neutrons ($< 0.5 \text{ eV}$) by two cadmium covers.

中文

The fission capture cross-section for ^{235}U is 1.4 barn at 2.5 MeV, increasing to 580 barn at thermal energies. Some of the neutrons emitted at 2.45 MeV from the cells will be captured by ^{235}U nuclei during their diffusion within the water bath. The fission fragments have a typical range of a few micrometres in U; those that escape the foil enter the plastic film and rupture polymer bonds, thereby creating a nuclear track that can be viewed microscopically after chemical etching with NaOH (ref. 13). (The track registration threshold of Lexan is such that the numerous α particles produced by the ^{238}U component of the U foils do not produce visible tracks.)

中文

The absolute neutron detection efficiency was measured with a ^{252}Cf source in a large water tank, with foil sandwiches placed relative to the source identically to those in Pons' laboratory, and was found to be 1.3×10^{-5} fission tracks per emitted neutron for a foil with no Cd cover; for those foils with Cd covers, the efficiency was a factor of about three lower.

中文

Fission track counts for each sandwich's pair of foils are shown in Fig. 1, the first number being the count for the foil without a Cd cover and the second being that with. There was no indication of an excess neutron signal from any of the cells; in fact, the control sandwich, adjacent to the water-tank wall, registered one of the highest fission-track counts, these being a measure of the dominant background source, cosmic-ray neutrons¹⁴. If we assume zero background, however, the fission track counts at cell 2-5 correspond to a mean neutron emission rate of 0.8 s^{-1} over the 67-h integration period, with a 99% confidence-level upper limit on neutron emission rate from cell

2-5 (based on counts in foils without Cd covers) of 1.8 s^{-1} , corresponding to a fusion power level of 0.9 pW. 中文

Pons has informed us that “no neutron detectors were ever placed in a tank when a cell in that tank was generating excess enthalpy”. 中文

Fusion Limits and Excess Heat Production

During the 831 h (live time) of monitoring γ -ray emissions from electrolytic cells in Pons' laboratory, no evidence was seen of radiation from any known $d + d$ (or $p + d$) fusion reaction. The upper limits placed on power from these reactions range between 10^{-12} and 10^{-6} W , which are many orders of magnitude lower than the sensitivity of the calorimetric measurements made by Pons' group; therefore, if a heat excess were to have occurred during our period of observation, one could conclude that no known fusion process contributed significantly to that excess. 中文

At one point, the D_2O in cell 2-1 was observed to boil for $\sim 2 \text{ h}$. Figure 5a shows an aggregate γ -ray spectrum for the 2.5 h that included this boiling episode, and Fig. 5b is the residual spectrum after subtraction of the previous 2.5 h of data. No spectral features of fusion are present in this residual spectrum. After completing our analysis, we were informed that we should not “reference these events as being due to release of excess thermal energy” (S. Pons, personal communication), because this boiling event may very well have a conventional explanation. Unfortunately we have not received any numerical data on excess heat production during the 831 h of our monitoring, so we are not able to correlate the absence of nuclear signatures with the presence of anomalous heat. 中文

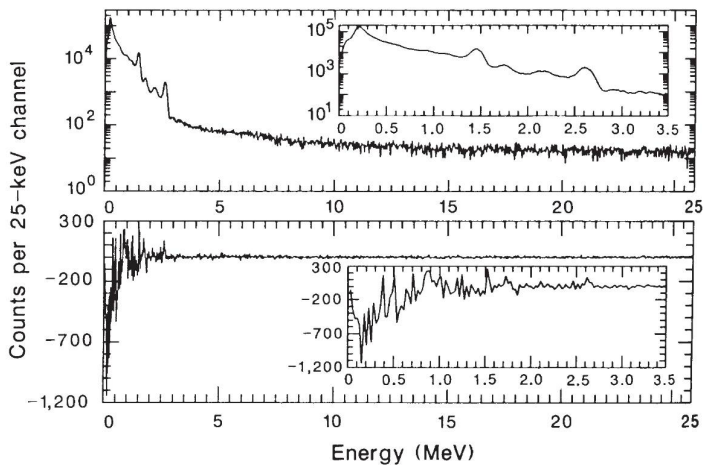


Fig. 5. *a*, γ -ray spectrum accumulated over a 2.5-h interval that included a ~ 2 -h period during which cell 2-1 was observed to boil the D_2O electrolyte. The inset is an expansion of the low-energy end of the spectrum. *b*, Residual spectrum after subtraction of the spectrum accumulated for the preceding 2.5 h. The negative excess at low energy is due to a slight (0.1%) gain shift that occurred during this 5-h period (these spectra were not rescaled).

中文

We were told, however, that “there was a two-hour segment in which there was excessive thermal release from cell 2-1... Unfortunately, your computer and detector were not under power at that time since they had not been reset from a power failure which had occurred in the lab” (S. Pons, personal communication). Although 48 h of data were indeed lost because of a lightning strike, we can nevertheless estimate mean upper limits for fusion power of $\sim 10^{-2}$ W for $d(d, p)t$ and 10^{-6} W for $d(d, n)^3He$ during this 2-h episode, because a fraction of the neutrons produced from these reactions would activate the ^{23}Na in the NaI detector, producing ^{24}Na . As ^{24}Na decays with a 15.0-h half-life, a spectral signature of a neutron burst would be present even several days after the burst. None was observed, leading to the conclusion that neither the $d(d, p)t$ nor the $d(d, n)^3He$ reaction was responsible for this anomalous heat burst. 中文

In addition, we later learned that a low-level, d.c. heat excess was observed during our monitoring period (S. Pons, EPRI Conference, University of Utah, 16 August 1989); if this is the case, this excess did

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Received 26 September 1989; accepted 30 January 1990.

References:

1. Fleischmann, M., Pons, S. & Hawkins, M. *J. electroanalyt. Chem.* **261**, 301-308(1989); and erratum, **263**, 187-188 (1989).
2. Petrasso, R. D. *et al. Nature* **339**, 183-185(1989); and erratum, **339**, 264 (1989).
3. Fleischmann, M., Pons, S. & Hoffman, R. J. *Nature* **339**, 667 (1989).
4. Petrasso, R. D. *et al. Nature* **339**, 667-669 (1989).
5. Wolf, K. *et al. Proc. Workshop on Cold Fusion* Santa Fe, May 23-25, (1989).
6. *Proc. Workshop on Cold Fusion* Santa Fe, May 23-25, (1989).
7. Zel'dovich, Ya. B. & Gershtein, S. S. *Sov. Phys. Usp.* **3**, 593-623 (1961).
8. Barkas, W. H. & Berger, M. J. in *Studies in Penetration of Charged Particles in Matter* 103-172 (Natn. Acad. Sci. Natn. Res. Council Publ'n 1133, Washington, DC, 1964).
9. Stelson, P. H. & McGowan, F. K. *Phys. Rev.* **110**, 489-506 (1958).
10. Fowler, J. L. & Brolley, J. E. Jr *Rev. mod. Phys.* **28**, 103-134 (1956).
11. Walling, C. & Simons, J. J. *Phys. Chem.* **93**, 4693-4696 (1989).
12. Berger, M. J. & Seltzer, S. M. in *Studies in Penetration of Charged Particles in Matter* 69-98 (Natn. Acad. Sci. Natn. Res. Council Publ'n 1133, Washington, DC, 1964).
13. Fleischer, R. L., Price, P. B. & Walker, R. M. *Nuclear Tracks in Solids* (University of California Press, Berkeley, 1975).
14. Hess, W. N., Canfield, E. H. & Lingenfelter, R. E. *J. Geophys. Res.* **66**, 665-677 (1961).
15. Seltzer, S. M. in *Monte Carlo Transport of Electrons and Photons* (eds Jenkins, T. M., Nelson, W. R. & Rindi, A.) (Plenum, New York, 1988).
16. Seltzer, S. M. & Berger, M. J. *Nucl. Instrum. Meth.* **B12**, 95-134 (1985).
17. Andersen, H. H. & Ziegler, J. F. *Hydrogen Stopping Powers and Ranges in all Elements* (Pergamon, New York, 1977).

Acknowledgements. We thank S. Pons, M. Anderson and M. Hawkins for their hospitality during our work in their laboratory. We thank K. Wolf for alerting us to the $t(d, n)^4\text{He}$ reaction that follows $d(d, p)t$, and K. Drexler for suggesting neutron detection via activation of ^{23}Na within our detector. We also thank R. Lloyd, W. Schier, D. Leavitt, F. Steinhausler and P. Bergstrom for valuable assistance, R. Petrasso for a careful review of an earlier manuscript, P. B. Price, M. Solarz, S. Barwick, R. Huber, R. Price and C. DeTar for helpful conversations, and

R. Cooper for technical assistance. This work was supported by the State of Utah. S.M.S. was supported by the Office of Health and Environmental Research, US Department of Energy.

庞斯/弗莱施曼电解池的中子、 γ 射线、电子和质子发射的上限

萨拉蒙等

全世界进行了许多实验来研究马丁·弗莱施曼和斯坦利·庞斯所声称的已在1989年利用台式电解实现了核聚变的断言，这篇文章中所报道的内容则提供了一些最具说服力的反面结果。迈克尔·萨拉蒙是与庞斯同一所学校（犹他大学）的物理学家，他得到了庞斯的允许，使用同一装置重复了那些实验。在彻底的尝试之后，萨拉蒙的团队没有找到“冷核聚变”的证据。庞斯声称在断电妨碍了计算机收集数据之后，确实有过剩热量产生。这一说法只会增加大家对最初断言的怀疑。这些实验曾一度为萨拉蒙招致诉讼威胁。 [英文](#)

犹他大学庞斯的实验室通过NaI探测器对庞斯和弗莱施曼使用的冷核聚变电解池放射出的 γ 射线进行了五个星期近乎连续的记录。已知的聚变反应的功率上限是 $10^{-12} \sim 10^{-6}$ W，在这个功率限制之上没有观察到任何聚变活动的证据。此外，中子径迹探测器表明，在67小时内，从其中任何一个冷核聚变电解池中发射出来的中子总数上限约为每秒一个中子。 [英文](#)

庞斯和弗莱施曼^[1]宣称在含有钽阴极和D₂O电解质（含0.1 M LiOD）的电解池中实现了氘核的“冷核聚变”，该反应产生了数量级为几瓦的过剩热量。他们的结论是基于以下理由得出的：缺乏已知的电化学反应机制来解释热量过剩以及略微高于本底的 γ 射线和中子的放射。上述数据的后者已经遭到批判^[2-4]，尽管存在大量的负面结果^[4]，但是在类似的电解池中产生氘的报告^[5]和一些实验室^[6]中电解池输入功率和输出功

率之间的差异仍然使得这场论战得以持续。 英文

已知的 $d + d$ 和 $d + p$ 反应和它们的能量产率 (Q) 为^[7]： $d(d, p)t(Q = 4.03 \text{ MeV})$ ； $d(d, n)^3\text{He} (Q = 3.27 \text{ MeV})$ ； $d(d, \gamma)^4\text{He} (Q = 23.85 \text{ MeV})$ ； $d(d, e^-)^4\text{He}$ (内转换) ($Q = 23.85 \text{ MeV}$)； $d(p, \gamma)^3\text{He} (Q = 5.49 \text{ MeV})$ 。 英文

在最初的声明发表之后数周，庞斯允许我们进入他的实验室，对从他运行的电解池中放射的所有辐射进行独立的测量。我们使用的是即时可用装置，将一个铅屏蔽的碘化钠 (NaI) 探测器 ($8 \text{ in} \times 4 \text{ in}$) 安装在他的电解池下方 (图1)，并在五周内几乎连续地对能量范围在 $0.1 \sim 25.5 \text{ MeV}$ 之内的 γ 射线进行了数据收集。此外，还将几个中子探测器放置在水槽中，与电解池相邻，它们对大约3天的时间段内的中子流进行了累计；这些中子探测器由夹在核径迹探测塑料薄膜之间的 ^{235}U 箔组成。 英文

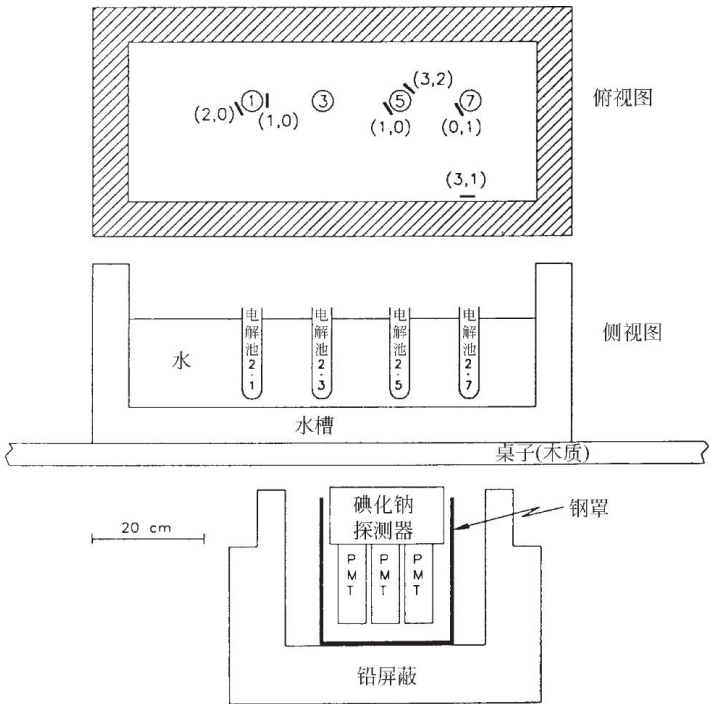


图1．电解池和 NaI 探测器布局的侧视图，以及相应位置（粗线部分）的可探测中子的三明治结构的电解池俯视图。电解池2-1，2-5和2-7的钽阴极直径/长度（以厘米为单位）分别为 $0.4/1.25$ 、 $0.4/10.0$ 和 $0.1/10.0$ ；电解池2-3有尺寸为 $0.1/10.0$ 的铂阴极。俯视图中每一个三明治结构显示的两个数字 (n, m) 分别是没有钨覆盖层和有钨覆盖层的铀箔塑料薄膜中记录的裂变

碎片数目。只分析每个箔中的一个塑料薄膜。[英文](#)

γ 射线的NaI探测

让四个开放的电解池（不进行气体收集）近乎连续地进行电解，同时NaI探测器在收集数据（5月9日至6月16日）。这些电解池由D₂O（0.1 M LiOD）电解质和铂阳极构成；阴极如图1所示。电解池在恒电流模式下运行，电流设定值在五周内是变动的。[英文](#)

NaI探测器系统被放置于支撑水槽和电解池的桌子下方，这样就不会对庞斯实验室里的其他研究活动形成干扰。电解池中产生的任何 γ 射线在被8 in $\times$ 4 in的NaI探测器探测到以前，都会先通过水、水槽和桌子。在光电峰中对 γ 射线进行探测的与能量有关的绝对效率（与在闪烁体中 γ 射线完全的能量转换相对应）可在一个独立实验室中用标准 γ 射线源进行确认，该独立实验室中可对水、水槽、桌子和探测器进行同样的配置和任意的去除。下面给出的辐射限是基于放置在电解池2-1处的源的源的绝对效率得到的。[英文](#)

将通过脉冲高度分析仪累积的 γ 谱数据在五周的时间内每隔半小时或者1小时（活时间）连续地下载到一台微机上，从而将瞬态信号的本底累积效应降至最低。设定了系统的增益以使0.1~25.5 MeV能量区间内的 γ 射线可以被记录下来。仪器运行785小时所得到的累积 γ 谱如图2a和2b所示。[英文](#)

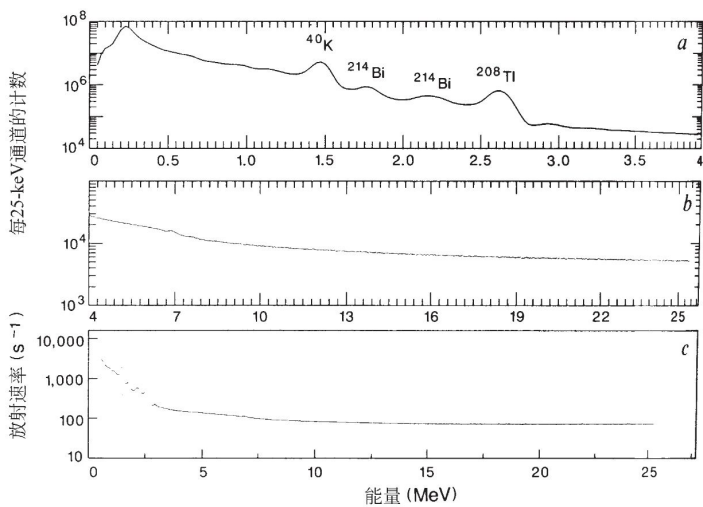


图2. a和b, 785小时的活时间收集的累积 γ 射线谱。主要的本底峰为 ^{40}K (1.4608 MeV)、 ^{214}Bi (1.7645 MeV) 和 ^{208}Tl (2.6146 MeV), 而一个约0.23 MeV处的背散射峰和一个约2.17 MeV处的宽峰源自 ^{214}Bi 的两个峰 (2.1186 MeV和2.2042 MeV)。探测器能量分辨率由 $R = 0.07E^{-1/2}(1 + 1.3/E)^{1/2}$ 给出, E 的单位为MeV, 式中的主导因素是探测器的最优分辨率, 附加的因素是由于脉冲高度分析仪的模数转换器的电荷积分输入存在噪音而导致的。系统电子部件的积分非线性在0.1~3.5 MeV的区间内小于0.1%, 在整个0.1~25.5 MeV区间为0.2%。对系统增益变化 (比如由于光电流漂移) 的监测表明, 在整个五周的时间内, 变化小于3.5%, 而在任何24小时区间内, 变化小于0.5%; c, 在0.1~25.5 MeV的范围内, 对全体 γ 射线进行搜寻得到的 γ 射线源的放射速率限值与能量的关系 (见正文部分)。在这些限值以内的信号被漏记的概率小于 10^{-3} 。 [英文](#)

逐条 γ 谱 (1,116条)、逐段时间 (每一段活时间积分的时长为0.5或1小时, 活时间共计831.0小时) 地寻找瞬时高于本底的 γ 射线信号。每条 γ 谱的本底要用若干 (10~50) 条连续的本底 γ 谱取平均而得到一个合成 γ 谱来求得, 然后, 从原始的 γ 谱中扣去此本底而得到“剩余谱”。对于每条 γ 谱进行这一扣除后就得到1,116条剩余谱。于是, 在小于10~50小时内任何瞬时的异常信号都会在剩余谱中以零点附近一片泊松涨落之上的正剩余的形式显示出来。持续时间更长的信号还可以通过对合成 γ 谱的集合进行相似的操作来寻找, 而且其灵敏度还更高些。 [英文](#)

为了能够对探测器系统的增益和消隐脉冲电平 (对应于能量为零的脉冲高度分析仪的通道) 的短暂变化进行校正, 通过把每一个单独的 γ 谱对 γ 射线本底进行拟合的方法来对增益和消隐脉冲电平进行确定。然后在扣除本底之前, 所有的 γ 谱被重新调节到通常具有零偏置的增益水平, 这样可以减小剩余 γ 谱中由增益或零点漂移或者两者兼而有之所带来的伪差。 [英文](#)

中子流的限值: $\text{d}(\text{d},\text{n})^3\text{He}$ 来自核聚变通道 $\text{d}(\text{d},\text{n})^3\text{He}$ 的中子具有2.45 MeV的初始动能和在水中4.9 cm的平均自由程, 由于中子热化, 它的自由程会缩减为0.4 cm。由于每一个电解池都被数英寸的水浴包围, 大多数放射出的中子会在周围的水浴中热化并通过 $\text{n}(\text{p}, \text{d})\gamma$ 反应产生2.22 MeV的 γ 射线; 蒙特卡洛计算表明, 对位于2-1电解池处的2.45 MeV的点中子源而言, 62%放射出的中子会被水浴中的氢捕获。通过一个Am-Be中子源测得, 绝对的光电峰探测效率 (对2-1电解池) 为 3.0×10^{-3} 。 [英文](#)

通过对2.0~2.4 MeV能量区间的剩余 γ 谱进行高斯拟合 (以2.2 MeV

为中心能量，方差由探测器分辨率确定），每一个剩余 γ 谱中都可以观察到一个位于2.2 MeV处的高于本底的 γ 射线信号。拟合幅值的频数分布以pW为核聚变功率的单位，如图3a所示。在这1,114个 γ 谱中，拟合出的最大幅值为10 pW。在这个分布（以及后面其他的分布）中我们排除了两个图谱，因为它们含有来自 ^{22}Na 和 ^{137}Cs 源的光电峰，这是由于其他人将这两种放射源带入实验室造成的。

英文

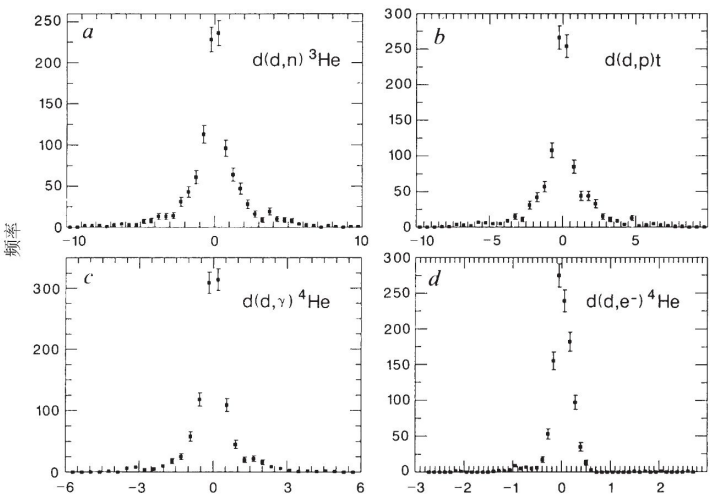


图3 . 对四个 $d + d$ 核聚变反应估算的速率。对于数据采集区间持续0.5~1小时的1,114条 γ 射线谱中的每一条，从信号中减去平均化的本底 γ 谱可以得到一条剩余 γ 谱。通过调节每一个反应的已知形式的 γ 射线谱的比例，对每一个剩余光谱进行拟合；拟合得到的数量级可以为正也可以为负。这里的图是所有1,114条 γ 谱的柱状图。在a和b中，速率以聚变的功率为单位（a: pW；b: mW）；c和d中，反应速率为通常使用的单位（c: s^{-1} ；d: 10^3 s^{-1} ）。每一个图中，柱状图大致呈现为零点附近的高斯分布，表明对于任何一个核聚变反应没有可测量的速率。

英文

质子流的限值： **$d(d, p)t$** 核聚变通道 $d(d, p)t$ ($Q = 4.03 \text{ MeV}$)是冷核聚变过程的一个最有可能的反应，这既是因为有过量氚产生的报告[5]，也是因为它的反应产物被固定在了铯电极中（3 MeV的质子在铯中的范围约为30 μm ；参考文献8），因此有可能避免“产生了瓦特量级的聚变功率却没有观察到粒子发射”的佯谬。事实上，一个强而明显的 γ 射线特征存在于这一反应中：3.02 MeV的质子导致铯同位素偶-偶核的库仑激发，退激发时它辐射出的0.37 MeV到0.56 MeV之间的辐射可以被NaI探测器以表1中给出的效率 η 探测到。这个表由参考文献9改编而来，列出了每一种铯同位素的E2（电四极） γ 射线的能量和100%同位素富集的样品的厚靶辐射产额（每微库仑质子的激发量），同时还假设了电解

池2-1为源的光电峰探测效率，并考虑到在钼阴极内部E2 γ 射线吸收的修正因子。图4显示了一个从暴露在源自范德格拉夫加速器的3.02 MeV质子束中的3 mm的天然钼靶所放射出的NaI γ 射线谱（希尔，个人交流）。在0.37 MeV、0.43 MeV和0.51 MeV处观察到了峰值，并且与预期的强度一致。

英文

表1. 3 MeV的质子在钼电极中的辐射产额

同位素 (E2 能量) (MeV)	同位素丰度	质子能量 (MeV)	激发/ μ C	NaI 探测器效率 η	钼的逃逸概率
$^{104}\text{Pd}(0.555)$	11.0	3.30	$5.08(0.16) \times 10^5$	2.3×10^{-3}	0.81
		2.40	$4.35(0.17) \times 10^4$		
$^{106}\text{Pd}(0.513)$	27.3	3.30	$7.47(0.18) \times 10^5$	2.3×10^{-3}	0.80
		3.00	$4.00(0.12) \times 10^5$		
		2.70	$1.98(0.06) \times 10^5$		
$^{108}\text{Pd}(0.433)$	26.7	3.30	$1.19(0.03) \times 10^6$	2.2×10^{-3}	0.77
		3.00	$7.02(0.19) \times 10^5$		
		2.70	$3.76(0.08) \times 10^5$		
$^{110}\text{Pd}(0.374)$	11.8	3.30	$1.82(0.04) \times 10^6$	2.1×10^{-3}	0.73
		3.00	$1.11(0.02) \times 10^6$		
		2.70	$6.15(0.13) \times 10^5$		

英文

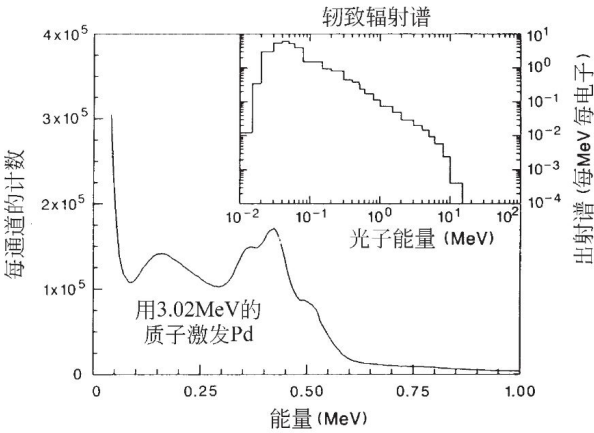


图4．来自钼同位素的电四极（E2） γ 射线峰，通过3.02 MeV的质子激发，用3 in $\times$ 3 in的NaI探测器测量。0.37 MeV、0.43 MeV和0.51 MeV处的三个峰构成了d(d, p)t反应清晰的 γ 射线特征（0.56 MeV处 ^{104}Pd 的第四个峰很弱，在这里难以看清）。它们共有的背散射峰在约0.16 MeV处。插图：从一个高36 cm、直径36 cm的水柱中心出射的在20 MeV处的电子的出射轫致辐射谱。对单个电子进行归一化，将 γ 射线流沿柱状体的表面积分；光谱下的面积对应于每电子1.1个光子，包括0.511 MeV的湮灭光子的 δ 函数导致的一小部分（没有在图中显示）。这个 γ 谱使用蒙特卡罗代码ETRAN^[15]得到，该代码使用最近发展的轫致辐射截面方法^[16]对耦合的电子-光子输运进行了处理。

英文

以NaI探测器的分辨率对这些峰强度进行卷积，并使用表1中的有效因子，对理论产生的 γ 谱按比例进行缩放以使其与每个剩余 γ 谱的0.362~0.613 MeV区域拟合最佳。1,114个拟合比例因子（以聚变功率的mW为单位）的频数分布示于图3b中。没有一个比例因子超过10 mW。这个限值与在这些电解池上进行的量热测量的灵敏度相似。

英文

通过认定以动能1.0 MeV放射出来的氚能够引发 $t(d, n)^4\text{He}$ 反应，可以确定这个通道更为严谨的限值。通过对钚中氚的能量范围内能量依赖反应的截面^[10]进行积分，假设晶格中d:Pu的比例为1:1，每发射一个氚引发 $d + t$ 聚变的概率为 4×10^{-5} 。（我们注意到1.0 MeV的氚核在氧化钚的晶格中通过反应 $t(d, n)^4\text{He}$ 产生一个中子的概率 p 可以表达为氚与钚之比（原子数之比） r 的函数： $p = a_0 + a_1 r + a_2 r^2$ ，其中 $a_0 = 9.63 \times 10^{-8}$ ， $a_1 = 4.48 \times 10^{-5}$ ， $a_2 = -5.40 \times 10^{-6}$ 。这个表达式是基于参考文献10中的核反应截面和文献17中的氢的遏止率得到的，其精度 $\leq 10^0\%$ ，在 $0.4 \leq r \leq 1.5$ 范围内有效。）蒙特卡罗计算显示，得到的约14 MeV（质心）的中子中，39%会热化并被水槽中的质子捕获，得到一个2.2 MeV的 γ 射线信号。从这一信号的缺失情况来看，我们得到核聚变功率幅值的上限为0.4 μW 。

英文

γ 射线流的限值： $d(d, \gamma)^4\text{He}$ ， $d(p, \gamma)^3\text{He}$ ，单能 γ 射线 通过将预期的23.85 MeV的 γ 射线谱线轮廓对剩余 γ 谱在23.6~24.1 MeV能量区间内进行拟合，来搜索来自反应 $d(d, \gamma)^4\text{He}$ 的23.85 MeV γ 射线。图3c显示了源发射速率分布的拟合结果；最大拟合速率为 5 s^{-1} ，对应的核聚变功率为20 pW。对 $d(p, \gamma)^3\text{He}$ 反应放出的5.49 MeV的 γ 射线也进行了类似的搜索；最大的源放射拟合速率 10 s^{-1} 对应于约10 pW的核聚变功率。

英文

在每个剩余 γ 谱中对整个0.1~25.5 MeV能量区间内高于本底的可能 γ 射线峰进行了总体搜寻。符合条件的可能情况需要有至少一个通道计数高于 3σ （ σ 为那个通道计数的传递泊松误差），并且延展到取样能量处 γ 射线峰的半高宽的临近通道计数和要大于 9σ 。找到的唯一可能的 γ 射线峰是由于 γ 谱增益不完善的缩放和平均本底零点不准而造成的；这些可以通过其邻近的正漂移和负漂移的数量级相同，以及在一个已知的本

底峰的位置过零点，来进行识别。没有发现其他的可能的 γ 射线峰。结合探测器效率，得到了 γ 射线放射速率限值和能量的相互关系（对电解池2-1而言），如图2c所示。 [英文](#)

内转换电子流的限值： $d(d, e^-)^4\text{He}$ 即使对于低原子量的核以及光子能量远高于电子质量的情形，内转换引起的核退激相对于辐射退激是被大大地抑制了的，仍有人认为冷核聚变实际上可以通过内转换发生^[11]，这一过程会产生携带有23.8 MeV动能的电子。 [英文](#)

图4显示了计算出的一个位于36 cm直径的水圆柱体中心各向同性的20 MeV电子点源所产生的轫致辐射光谱（假定在钨阴极内有约4 MeV的损失^[12]）。归一化到一个源电子，光谱拥有的积分面积为每电子1.1个光子。这个轫致辐射光谱，经过探测器效率修正后，调整其比例以得到对每一剩余光谱的最佳拟合，从而给出每一个光谱最佳拟合的轫致辐射光子的数目。图3d显示对应于拟合的轫致辐射光子数目的电子发射速率频数分布。电子发射速率的最大拟合值为每秒 2.6×10^3 个电子，对应于核聚变功率水平为10 nW。 [英文](#)

使用核径迹探测器的中子探测

通过由富集 ^{235}U （80%）铀箔和核径迹探测塑料（即莱克森聚碳酸酯）组成的中子探测三明治结构，得到了一个明显小于10 pW的上限，这个值是根据前面讨论的基于67小时区间（5月16日至19日）的平均中子产率得到的。六个三明治结构被安装在了含有电解池的水槽中（图1）；每一个含有两层铀箔，每一层铀箔面积约为1.4 cm²，质量约为0.078 g，夹在两层0.01 in厚的莱克森聚碳酸酯之间。两片铀箔之一用两层镉屏蔽掉慢中子（<0.5 eV）。 [英文](#)

^{235}U 的裂变捕获截面在2.5 MeV处为1.4靶恩，在热能下增大到580靶恩。一些从电解池中放射的2.45 MeV的中子在水浴里扩散期间会被 ^{235}U 捕获。裂变碎片在铀中有一个数微米的长度范围；那些逃离铀箔的裂变碎片会进入塑料薄膜并破坏高分子化学键，从而产生一个核径迹，该径迹经NaOH腐蚀后可以通过显微镜观察到（参考文献13）。（莱克森聚碳酸酯的径迹记录阈值使得铀箔中的 ^{238}U 组分产生的为数众多的 α

粒子不会产生可见的径迹。) [英文](#)

通过一个位于大水槽中的 ^{252}Cf 源对绝对的中子探测效率进行了测量，箔的三明治结构相对于源的放置位置与庞斯实验室的装置位置相同，结果在没有镉覆盖层的箔，每个放射的中子有 1.3×10^{-5} 个裂变径迹；对那些有镉覆盖层的箔，效率变为原来的 $\frac{1}{3}$ 。 [英文](#)

每一对由薄膜组成的三明治结构的裂变径迹计数如图1所示，第一个数字是没有镉覆盖层的箔，第二个对应有镉覆盖层的箔。没有迹象表明从任何一个电解池中曾放射出电中子本底高出1个中子的信号；实际上在临近水槽壁、用于对照的三明治结构中，记录到一个最高的裂变径迹计数，这些是对主要的本底源——宇宙射线中子^[14]的测量。然而，如果我们假定本底为零，电解池2-5的裂变径迹计数在67小时积分区间内对应的平均中子发射速率就为 0.8 s^{-1} ，来自电解池2-5的中子放射速率的上限置信水平为99%，（基于没有镉覆盖层的箔所得的计数）为 1.8 s^{-1} ，对应的核聚变功率水平为 0.9 pW 。 [英文](#)

庞斯已经告知我们“当水槽中的电解池产生过剩焓时，水槽中并没有放置过中子探测器”。 [英文](#)

核聚变限值和过剩热量的产生

在庞斯实验室中监测电解池 γ 射线放射的831小时（活时间）期间，没有发现任何已知的 $d + d$ （或 $p + d$ ）核聚变反应辐射的证据。这些反应的功率上限在 10^{-12} W 到 10^{-6} W 之间，这比庞斯研究组进行的量热测量的灵敏度低很多个数量级；因此，如果在我们的观察期间发生热量过剩，我们能够得出的结论是，没有已知的核聚变过程对这一过剩有明显贡献。 [英文](#)

我们曾一度观察到电解池2-1中的 D_2O 沸腾了约2小时。图5a显示了包括这个沸腾过程的2.5小时的累积 γ 射线谱，图b是减去沸腾开始之前2.5小时的数据后的剩余 γ 谱，剩余 γ 谱没有出现核聚变的 γ 谱特征。在完成我们的分析之后，我们被告知我们不应该“把这些事件归因于有过量热能释放”（庞斯，个人交流），因为对这个沸腾的事件可以有一个很好的

传统解释。不幸的是，在我们监测的831小时期间，我们并没有获得任何关于过剩热量产生的计算数据，所以我们不能够将核信号的缺失与异常热量的存在关联起来。

英文

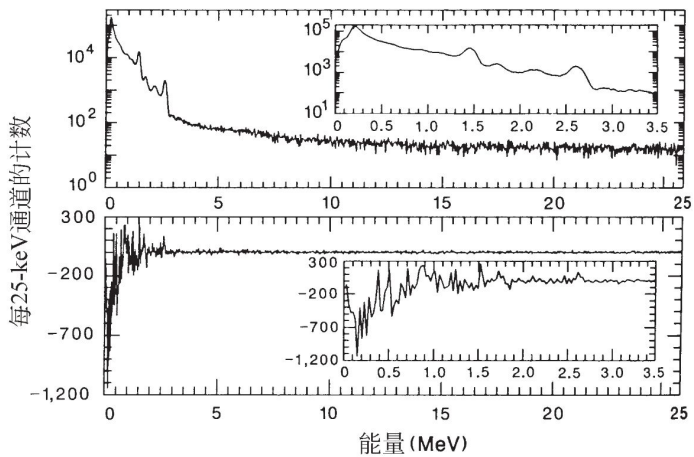


图5 . *a*，累积2.5小时的 γ 射线谱。其中包括一个约2小时的区间，在此期间在电解池2-1中观察到了 D_2O 电解质沸腾。插图是对 γ 谱低能端的放大。*b*，扣除沸腾开始之前2.5小时累积的 γ 谱之后的剩余 γ 谱。低能量处的负盈余是源于发生在整个5小时期间的一个微小的（0.1%）增益漂移（这些 γ 谱没有经过再标定）。

英文

然而，我们被告知“曾经有两个小时的时间段内电解池2-1有过剩的热量释放……不幸的是，当时你们的计算机和探测器并没有在工作，因为在实验室发生断电之后，它们没有得到重启”（庞斯，个人交流）。尽管因为雷击，48小时的数据确实丢失了，然而我们能估算出在这2小时的时段内，核聚变能量的平均上限对于 $d(d, p)t$ 反应约为 10^{-2} W，对于 $d(d, n)^3He$ 反应为 10^{-6} W，因为这些反应产生的中子的一部分会活化NaI探测器中的 ^{23}Na ，从而产生 ^{24}Na 。由于 ^{24}Na 以15小时的半衰期进行衰变，一个猝发中子的光谱信号在猝发之后的数天还可以观察到。由于什么也没有观察到，我们得出了以下结论，即不论是 $d(d, p)t$ 还是 $d(d, n)^3He$ 反应都不是这一异常的猝发热量的原因。

英文

另外，我们后来知道，在我们的监测期间观察到了一个低水平的热量过剩（庞斯，美国电力科学研究院（EPRI）会议，犹他大学，1989年8月16日）；如果这是事实，这一过剩并非源自已知的核过程。

英文

文

(李琦 翻译；李兴中 审稿)

Positioning Single Atoms with a Scanning Tunnelling Microscope

D. M. Eigler and E. K. Schweizer

The scanning tunnelling microscope was invented in the early 1980s as a tool for imaging the surfaces of materials at atomic resolution. As its needle-like metal tip moves just above the surface, electrons can jump the gap to produce an electrical current that changes as the gap size varies, offering a topographic map. In the late 1980s it became clear that electrical pulses applied to the tip could remove or alter the surface material. Here Don Eigler and Eric Schweizer at IBM's research laboratories in California show that the tip can be used to drag individual xenon atoms over a surface and position them at will. Their spelling of the company name in 35 atoms became an icon of nanotechnology. [中文](#)

Since its invention in the early 1980s by Binnig and Rohrer^{1,2}, the scanning tunnelling microscope (STM) has provided images of surfaces and adsorbed atoms and molecules with unprecedented resolution. The STM has also been used to modify surfaces, for example by locally pinning molecules to a surface³ and by transfer of an atom from the STM tip to the surface⁴. Here we report the use of the STM at low temperatures (4 K) to position individual xenon atoms on a single-crystal nickel surface with atomic precision. This capacity has allowed us to fabricate rudimentary structures of our own design, atom by atom. The processes we describe are in

principle applicable to molecules also. In view of the device-like characteristics reported for single atoms on surfaces^{5,6}, the possibilities for perhaps the ultimate in device miniaturization are evident. [中文](#)

THE tip of an STM always exerts a finite force on an adsorbate atom. This force contains both Van der Waals and electrostatic contributions. By adjusting the position and the voltage of the tip we may tune both the magnitude and direction of this force. This, taken together with the fact that it generally requires less force to move an atom along a surface than to pull it away from the surface, makes it possible to set these parameters such that the STM tip can pull an atom across a surface while the atom remains bound to the surface. Our decision to study xenon on nickel (110) was dictated by the requirement that the corrugations in the surface potential be sufficiently large for the xenon atoms to be imaged without inadvertently moving them, yet sufficiently small that, when desired, enough lateral force could be exerted to move xenon atoms across the surface. [中文](#)

The experiments were performed using an STM contained in an ultra-high-vacuum system and cooled to 4 K. The entire chamber housing the microscope was cooled to 4 K, which so reduced the contamination rate of the sample surface through adsorption of residual gases that no measurable contamination occurred over weeks. The stability of the sample and of the microscope due to the low temperature are such that one may perform experiments on a single atom for days at a time. This stability proved to be an operational necessity for performing these experiments. This notwithstanding, it is important to realize that the process that we describe for sliding atoms on a surface is fundamentally temperature independent. [中文](#)

The nickel sample was processed by cycles of argon-ion sputtering, annealing in a partial pressure of oxygen to remove surface carbon,

and flash annealing. After cooling to 4 K the sample was imaged with the STM and found to be of acceptable quality. Figure 1a is an image of the surface taken under constant-current scanning conditions after dosing with xenon to the desired coverage. This image was obtained with a tip bias voltage of 0.010 V relative to the sample, and a tunnel current of 10^{-9} A. Each xenon atom appears as a 1.6-Å-high bump on the surface, apparently at random locations. At this gap impedance the interaction of the xenon with the tip is sufficiently weak to leave the xenon essentially unperturbed during the imaging process. 中文

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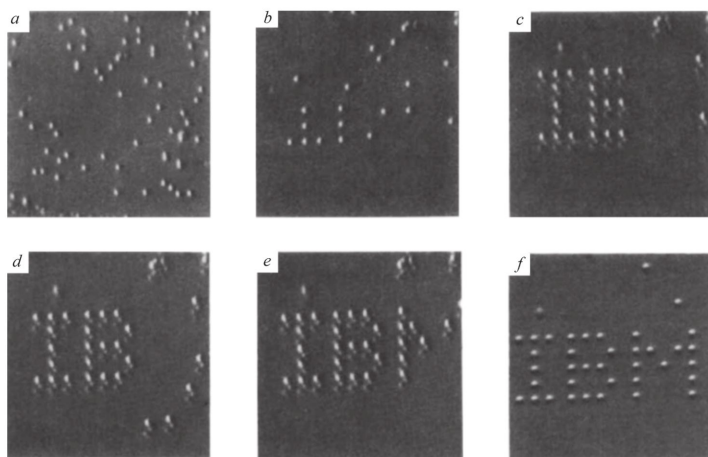


Fig. 1. A sequence of STM images taken during the construction of a patterned array of xenon atoms on a nickel (110) surface. Grey scale is assigned according to the slope of the surface.

The atomic structure of the nickel surface is not resolved. The $\langle 1\bar{1}0 \rangle$ direction runs vertically. *a*, The surface after xenon dosing. *b-f*, Various stages during the construction. Each letter is 50 Å from top to bottom. 中文

To move an atom we follow the sequence of steps depicted in Fig. 2. We begin by operating the microscope in the nonperturbative imaging mode described above to locate the atom to be moved and to target its destination. We stop scanning and place the tip directly above the atom to be moved (*a*). We then increase the tip-atom interaction by lowering the tip toward the atom (*b*); this is achieved by changing the required tunnel current to a higher value, typically in the range $1-6 \times 10^{-8}$ A, which causes the tip to move towards the atom until the

new tunnel current is reached. We then move the tip under closed-loop conditions across the surface, (c), at a speed of 4 Å per second to the desired destination (d), dragging the xenon atom with it. The tip is then withdrawn (e) by reducing the tunnel current to the value used for imaging. This effectively terminates the attraction between the xenon and the tip, leaving the xenon bound to the surface at the desired location. 中文

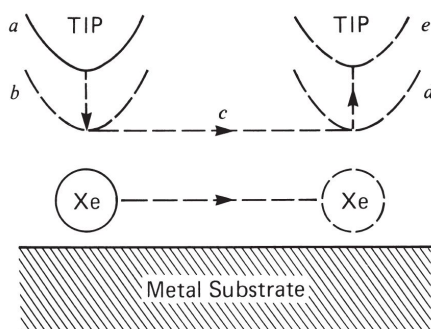


Fig. 2. A schematic illustration of the process for sliding an atom across a surface. The atom is located and the tip is placed directly over it (a). The tip is lowered to position (b), where the atom–tip attractive force is sufficient to keep the atom located beneath the tip when the tip is subsequently moved across the surface (c) to the desired destination (d). Finally, the tip is withdrawn to a position (e) where the atom–tip interaction is negligible, leaving the atom bound to the surface at a new location. 中文

Figure 1 is a sequence of images taken during our first construction of a patterned array of atoms, and demonstrates our ability to position atoms with atomic precision. The exact periodicity of the xenon spacing is derived from the crystalline structure of the underlying nickel surface (which is not resolved in Fig. 1). The nickel (110) surface has an unreconstructed rectangular unit cell and is oriented such that the short dimension of the rectangular surface unit cell runs vertically in the image. The xenon atoms are spaced on a rectangular grid which is four nickel unit cells long horizontally and five unit cells long vertically, corresponding to 14×12.5 Å. 中文

Although the STM tip is made from tungsten wire, the true chemical identity and the structure of the outermost atoms of the tip are not

known to us. We find that for any given tip and bias voltage, there is a threshold height below which the tip must be located to be able to move xenon atoms parallel to the rows of nickel atoms, and a lower threshold height for movement perpendicular to the rows of nickel atoms. This is consistent with a simple model wherein the xenon interaction with the metal surface is approximated by pairwise interactions with the individual nickel atoms. Simple investigations showed that the magnitude or sign of the applied voltage had no significant effect on the threshold tip height. This suggests that the dominant force between the tip and the xenon atom is due to the Van der Waals interaction, but this tentative conclusion requires further investigation. [中文](#)

In Fig. 3 we show a sequence of images demonstrating how a simple structure, the linear multimer, may be fabricated using this process. First we slide xenon atoms into a chosen row of nickel atoms. We next slide a xenon atom along the row to a position where it will bind with a neighbouring xenon to form a dimer. We repeat the process, forming a linear trimer, then a linear tetramer, and so on. From these images we find that the linear xenon chain along the $\langle 1\bar{1}0 \rangle$ direction of the nickel (110) surface is stable, the xenon atoms occupying every other surface unit cell along a row of nickel atoms. Attempts to pack the xenon atoms closer were unsuccessful. We find the xenon–xenon spacing along the row to be uniform (excluding end effects) to within 0.2 Å. [中文](#)

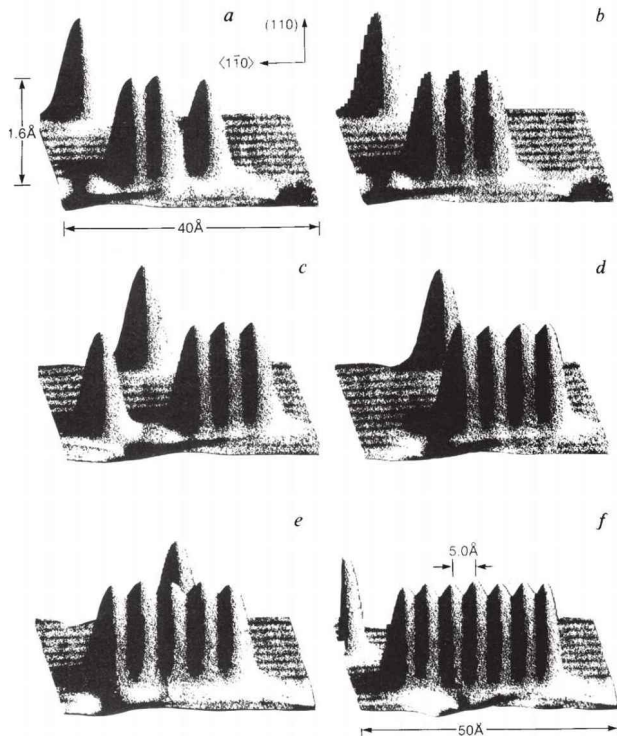


Fig. 3. Various stages in the construction of a linear chain of xenon atoms on the nickel (110) surface. The individual xenon atoms appear as 1.6-Å-high protrusions in these images. The rows of nickel atoms are visible as alternating light and dark stripes. Several point defects are visible in the nickel surface. *a*, The assembled xenon dimer. To the right of the dimer, a xenon atom has been moved into position for forming a xenon trimer. *b*, Formation of the xenon linear trimer. *c-f*, Various stages in construction of the linear heptamer, a process that can be completed in an hour. The xenon atoms are 5 Å apart, occupying every other unit cell of the nickel surface. 中文

We anticipate that there will be a limiting class of adsorbed atoms and molecules that may be positioned by this method. Many new avenues of investigation are open to us. It should be possible to assemble or modify certain molecules in this way. We can build novel structures that would otherwise be unobtainable. This will allow a new class of surface studies that use the STM both to fabricate overlayer structures and to probe their properties. The prospect of atomic-scale logic circuits and other devices is a little less remote. 中文

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Received 17 January; accepted 9 March 1990.

References:

1. Binnig, G., Rohrer, H., Gerber, Ch. & Weibel, E. *Appl. Phys. Lett.* **40**, 178-180 (1982).
2. Binnig, G., Rohrer, H., Gerber, Ch. & Weibel, E. *Phys. Rev. Lett.* **49**, 57-61 (1982).
3. Foster, J. S., Frommer, J. E. & Arnett, P. C. *Nature* **331**, 324-326 (1988).
4. Becker, R. S., Golovchenko, J. A. & Swartzentruber, B. S. *Nature* **325**, 419-421 (1987).
5. Lyo, I.-W. & Avouris, P. *Science* **245**, 1369-1371 (1989).
6. Bedrossian, P., Chen, D. M., Mortensen, K. & Golovchenko, J. A. *Nature* **342**, 258-260 (1989).

Acknowledgements. This work would not have occurred were it not for the patient and visionary management of the IBM Research Division.

用扫描隧道显微镜定位单个原子

艾格勒，施魏策尔

扫描隧道显微镜发明于20世纪80年代初，是在原子级分辨率上对材料表面成像的一种工具。随着它的针状金属尖端在材料表面上移动，电子通过隧道效应穿过针尖与样品表面的间隙从而产生电流，电流强度随间隙大小不同而发生改变，从而描绘出材料表面的形貌。20世纪80年代后期，通过在探针尖端应用电脉冲可以移动或改变材料表面。本文中加利福尼亚IBM研究实验室的唐·艾格勒和埃里克·施魏策尔描述了利用针尖在材料表面拖动单个氦原子并进行任意定位。他们用35个原子拼写出的公司名称成为纳米技术的一个标志。

[英文](#)

自从宾尼希和罗雷尔在20世纪80年代初发明扫描隧道显微镜（STM）^[1,2]以来，它就以空前的分辨率为我们提供了关于材料表面和被吸附原子及分子的图像。STM还被用来修饰表面，例如将分子局部地固定在表面上^[3]，以及将一个原子从STM的探针尖端转移到材料表面^[4]。本文中我们报道了在低温下（温度为4 K）利用STM以原子级精度把单个氦原子定位在单晶镍表面上。这种能力使我们可以逐个原子地制作我们设计的基本结构。我们所描述的这个过程原则上同样适用于分子。从已报道的表面上单个原子的独特性质^[5,6]来看，最终实现功能器件最小化的可能性是显而易见的。

[英文](#)

STM的探针尖端总是对被吸附原子施加一个有限的力。这个力中同时包含着范德华力和静电力的贡献。通过调整针尖的位置和电压，我们可以调节此力的大小和方向。此外，考虑到沿着表面移动原子比将其拖离表面更省力这一事实，我们可以通过设置这些参数，使STM针尖拉动

一个原子穿过表面的同时，仍保持该原子结合在表面上。出于以下原因我们决定研究镍（110）面上的氙：表面电势起伏可以足够大，使得我们可以对氙原子成像，而又不会不经意地移动它们；另外在需要时，表面电势的起伏还可以足够小，使得我们可以施加足够的侧向力在表面上移动氙原子。 [英文](#)

实验在一台含有超高真空系统的STM上进行，同时系统被冷却至4 K。将容纳显微镜的整个样品室冷却至4 K，通过吸收残余气体可以降低样品表面的污染速率，使其在几星期内没有可测量到的污染发生。低温保证了样品和显微镜的稳定性，这使得人们可以对单个原子进行一次长达数天的实验。我们已证明这一稳定性是进行实验的必要操作条件。尽管如此，还要注意到，我们所描述的在表面上移动原子的过程本质上是不依赖于温度的。 [英文](#)

我们利用氙离子对镍样品进行反复喷溅，在氧分压中退火以除去镍表面的碳，且经快速退火完成样品处理。在冷却至4 K后，用STM对样品成像，确定其表面足够清洁。图1a是将氙添加到预期覆盖度后在恒定电流扫描条件下获得的表面图像。该图像是在相对于样品0.010 V的针尖偏压和 10^{-9} A的隧道电流条件下获得的。每个氙原子看起来就像表面上一个1.6 Å高的团块，并且明显地处于随机位置。在隧道结阻抗的条件下，氙原子与针尖的相互作用非常弱，因此在成像过程中，氙原子基本不受到扰动。 [英文](#)

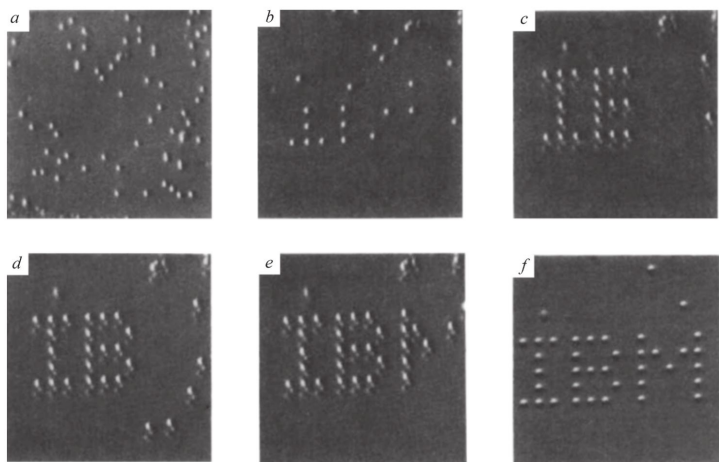


图1．在镍（110）表面上构建排列成图案的氙原子阵列过程中拍摄的一系列STM图像。根据表面的斜率确定灰度。对镍表面的原子结构未进行分辨。 $\langle 1\bar{1}0 \rangle$ 方向为垂直指向。*a*，加入氙之后

的表面。 $b\sim f$ ，构建过程中的各个阶段。每个字母从顶部到底部是50 Å。

英文

按照图2所示的一系列步骤来移动单个原子。用上文所描述的无干扰成像模式操作显微镜，找到待移动原子，瞄准其目的地。然后停止扫描，将针尖置于待移动原子的正上方（ a ）。接着，我们通过将针尖向着原子下降（ b ）来增加针尖-原子之间的相互作用；通过增大所需隧道电流值，一般是达到 1×10^{-8} A至 6×10^{-8} A的范围时，即可实现这一点，这一电流范围使得针尖移向原子，直至达到新的隧道电流值。接着，我们在闭合回路的条件下移动针尖穿过表面（ c ），以4 Å/s的速度移向目的地（ d ），同时始终拖着氙原子。然后，通过将隧道电流减少到成像所需的值使针尖后撤（ e ）。这就有效地终止了氙与针尖之间的吸引力，将氙留在了表面上所预期的位置。

英文

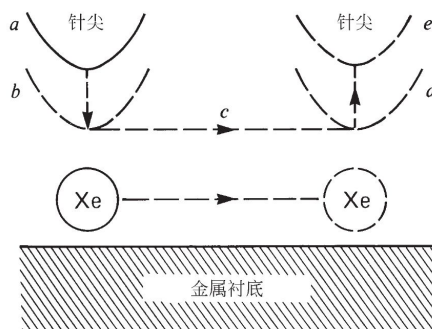


图2．在表面移动原子过程的示意图。定位原子，针尖位于其正上方（ a ）。将针尖降低到一定位置（ b ），在针尖随后移过表面（ c ）到达目的地（ d ）期间，原子-针尖之间的吸引力足以维持原子固定在针尖下方。最后，将针尖后撤到一个位置（ e ），此时原子-针尖相互作用小到可忽略，把原子留在表面上的一个新位置。

英文

图1是在我们首次构建排列成图案的氙原子阵列过程中所拍摄的一系列图像，证明了我们能够以原子级精度放置原子。氙原子间距的精确周期可以利用背景镍表面的晶体结构（在图1中没有进行分辨）得到。镍（110）表面有一个未重现出来的矩形单胞，其方向为矩形表面单胞的短边处于图像中的垂直方向。这些氙原子间隔排列在一个矩形网格中，水平方向上为四个镍单胞长，垂直方向上为五个晶胞长，面积相当于 $14\text{ Å}\times 12.5\text{ Å}$ 。

英文

尽管STM针尖是用钨丝制成的，但是我们并不知道针尖最外围原子的真实化学特性与结构。我们发现对于任何给定的针尖和偏压，都存在

着一个临界高度，针尖必须位于这个高度以下才能沿着平行于镍原子阵列的方向移动氙原子，还存在着一个垂直于镍原子阵列移动时的更低临界高度。这与如下的简单模型是相一致的，其中氙与金属表面的相互作用近似于单个镍原子的成对相互作用。简单的研究表明外加电压的大小和方向对于临界针尖高度没有显著影响。这意味着针尖与氙原子之间的主要作用力应归结为范德华相互作用，但是这个初步结论还需要进一步的研究。 [英文](#)

在图3中，我们给出了一系列图像来说明怎样利用这个过程来搭建一个简单结构，即线型多聚体。首先，将氙原子滑入一个选定的镍原子行中。接下来，沿着该行滑动一个氙原子使其到达一个能与邻近氙原子连接形成二聚体的位置。我们重复这一过程，形成一个线型三聚体，接着是线型四聚体，依此类推。从这些图像中，我们发现沿着镍原子（110）表面上 $\langle 1\bar{1}0 \rangle$ 方向的线型氙原子链是稳定的，氙原子沿着一行镍原子间隔占据表面单胞。使氙原子堆积得更近的尝试是不成功的。我们发现沿着行方向的氙-氙间距是相同的（除了末端效应以外），误差在 $0.2 \text{ \AA}$ 以内。 [英文](#)

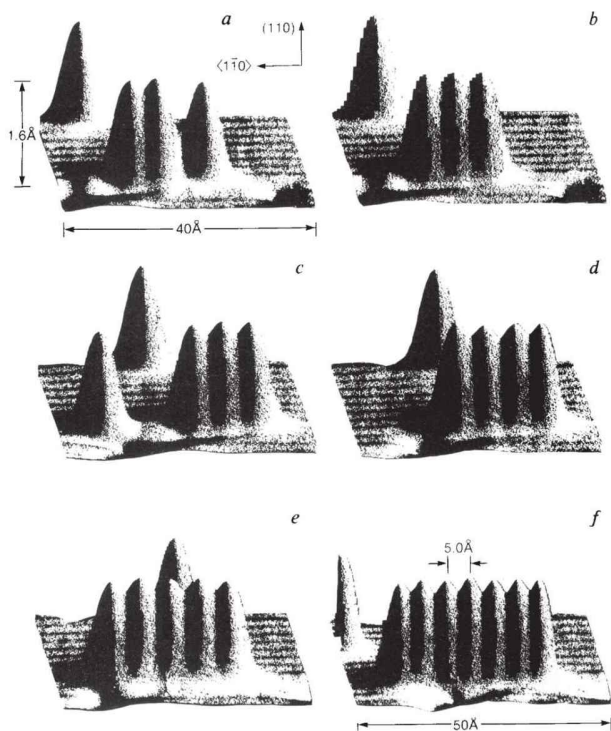


图3 . 在镍（110）表面上构建线型氙原子链的各个阶段。在这些图像中单个氙原子显示为 $1.6 \text{ \AA}$ 高的突出物。镍原子行看起来犹如明暗交替的条纹。可以看到镍表面有若干处点缺陷。*a* , 已装配好的氙原子二聚体。在二聚体的右侧，一个氙原子已进入恰当的位置，准备形成一个三聚体。*b* , 氙原子线型三聚体的形成。*c~f* , 构建线形七聚体的各个阶段，这个过程能够在一小时内完成。氙原子间距为 $5 \text{ \AA}$, 各自占据相邻的镍表面单胞。 [英文](#)

我们预期将会有一类特定的被吸附的原子和分子可以用这种方法来定位。很多新的研究途径展现在我们面前。应该有可能以这种方式来组装或修饰某些分子。我们能够构建出用其他办法无法得到的新型结构。这将引出一系列新的表面研究工作，即利用STM构建吸附层结构并探查其性质。这样，离实现原子尺度的逻辑电路和其他器件的梦想又近了一步。 [英文](#)

（王耀杨 翻译；王琛 审稿）

Light-emitting Diodes Based on Conjugated Polymers

J. H. Burroughes *et al.*

After the discovery of electrically conducting polymers in the 1970s, subsequent work identified several organic polymers with semiconducting electrical behaviour. One of them—poly (*p*-phenylene vinylene) or PPV—was prepared by Richard Friend and his co-workers at Cambridge. Here they show that PPV can be used in polymer light-emitting diodes (LEDs), which emit a yellowish light when an electrical current is passed through them. In conventional inorganic LEDs, new colours demand new materials. But the wavelength of light from polymer LEDs can be tuned by chemically modifying the polymer backbone. Such devices, spanning the entire visible spectrum, are now used in prototype commercial light-emitting displays. Being all-plastic, they can be rolled up like paper and fabricated using cheap printing technologies. [中文](#)

Conjugated polymers are organic semiconductors, the semiconducting behaviour being associated with the π molecular orbitals delocalized along the polymer chain. Their main advantage over non-polymeric organic semiconductors is the possibility of processing the polymer to form useful and robust structures. The response of the system to electronic excitation is nonlinear—the injection of an electron and a hole on the conjugated chain can lead

to a self-localized excited state which can then decay radiatively, suggesting the possibility of using these materials in electroluminescent devices. We demonstrate here that poly(*p*-phenylene vinylene), prepared by way of a solution-processable precursor, can be used as the active element in a large-area light-emitting diode. The combination of good structural properties of this polymer, its ease of fabrication, and light emission in the green-yellow part of the spectrum with reasonably high efficiency, suggests that the polymer can be used for the development of large-area light-emitting displays. [中文](#)

THERE has been long-standing interest in the development of solid-state light-emitting devices. Efficient light generation is achieved in inorganic semiconductors with direct band gaps, such as GaAs, but these are not easily or economically used in large-area displays. For this, systems based on polycrystalline ZnS have been developed, although low efficiencies and poor reliability have prevented large-scale production. Because of the high photoluminescence quantum yields common in organic molecular semiconductors, there has long been interest in the possibility of light emission by these organic semiconductors through charge injection under a high applied field (electroluminescence)¹⁻⁷. Light-emitting devices are fabricated by vacuum sublimation of the organic layers, and although the efficiencies and selection of colour of the emission are very good, there are in general problems associated with the long-term stability of the sublimed organic film against recrystallization and other structural changes. [中文](#)

One way to improve the structural stability of these organic layers is to move from molecular to macromolecular materials, and conjugated polymers are a good choice in that they can, in principle, provide both good charge transport and also high quantum efficiency for the

luminescence. Much of the interest in conjugated polymers has been in their properties as conducting materials, usually achieved at high levels of chemical doping⁸, and there has been comparatively little interest in their luminescence. One reason for this is that polyacetylene, the most widely studied of these materials, shows only very weak photoluminescence. But conjugated polymers that have larger semiconductor gaps, and that can be prepared in a sufficiently pure form to control non-radiative decay of excited states at defect sites, can show high quantum yields for photoluminescence. Among these, poly(*p*-phenylene vinylene) or PPV can be conveniently made into high-quality films and shows strong photoluminescence in a band centred near 2.2 eV, just below the threshold for π to π^* interband transitions^{9,10}. 中文

We synthesized PPV (I) using a solution-processable precursor polymer (II), as shown in Fig. 1. This precursor polymer is conveniently prepared from α,α' -dichloro-*p*-xylene (III), through polymerization of the sulphonium salt intermediate (IV)¹¹⁻¹³. We carried out the polymerization in a water/methanol mixture in the presence of base and, after termination, dialysed the reaction mixture against distilled water. The solvent was removed and the precursor polymer redissolved in methanol. We find that this is a good solvent for spin-coating thin films of the precursor polymer on suitable substrates. After thermal conversion (typically ≥ 250 °C, *in vacuo*, for 10 h), the films of PPV (typical thickness 100 nm) are homogeneous, dense and uniform. Furthermore, they are robust and intractable, stable in air at room temperature, and at temperatures > 300 °C in a vacuum¹¹. 中文

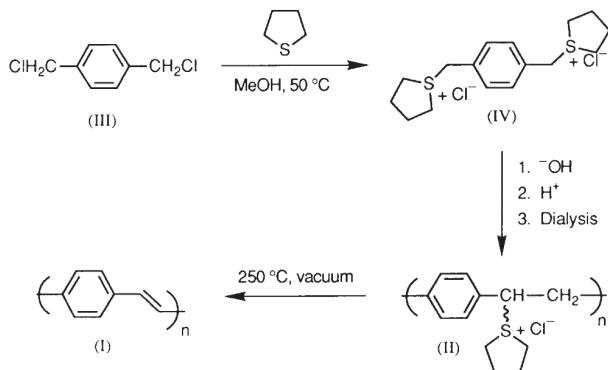


Fig. 1. Synthetic route to PPV. 中文

Structures for electroluminescence studies were fabricated with the PPV film formed on a bottom electrode deposited on a suitable substrate (such as glass), and with the top electrode formed onto the fully converted PPV film. For the negative, electron-injecting contact we use materials with a low work function, and for the positive, hole-injecting contact, we use materials with a high work function. At least one of these layers must be semi-transparent for light emission normal to the plane of the device, and for this we have used both indium oxide, deposited by ion-beam sputtering¹⁴ and thin aluminium (typically 7–15 nm). We found that aluminium exposed to air to allow formation of a thin oxide coating, gold and indium oxide can all be used as the positive electrode material, and that aluminium, magnesium silver alloy and amorphous silicon hydrogen alloys prepared by radiofrequency sputtering are suitable as the negative electrode materials. The high stability of the PPV film allows easy deposition of the top contact layer, and we were able to form this contact using thermal evaporation for metals and ion-beam sputtering for indium oxide. 中文

Figures 2 and 3 show typical characteristics for devices having indium oxide as the bottom contact and aluminium as the top contact. The threshold for substantial charge injection is just below 14 V, at a field of $2 \times 10^6 \text{ V cm}^{-1}$, and the integrated light output is approximately linear with current. Figure 4 shows the spectrally resolved output for a

device at various temperatures. The spectrum is very similar to that measured in photoluminescence, with a peak near 2.2 eV and well resolved phonon structure^{9,10}. These devices therefore emit in the green–yellow part of the spectrum, and can be easily seen under normal laboratory lighting. The quantum efficiency (photons emitted per electron injected) is moderate, but not as high as reported for some of the structures made with molecular materials²⁻⁷. The quantum efficiencies for our PPV devices were up to 0.05%. We found that the failure mode of these devices is usually associated with failure at the polymer/thin metal interface and is probably due to local Joule heating there. [中文](#)

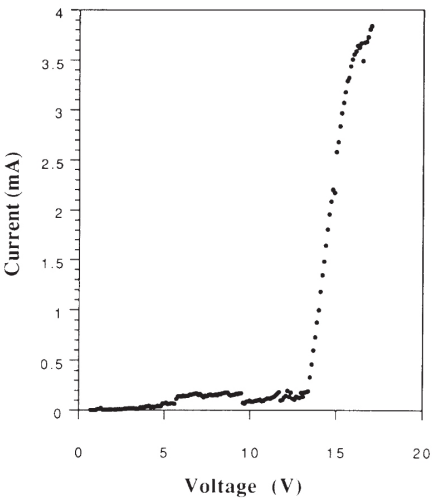


Fig. 2. Current–voltage characteristic for an electroluminescent device having a PPV film 70 nm thick and active area of 2 mm², a bottom contact of indium oxide, and a top contact of aluminium. The forward-bias regime is shown (indium oxide positive with respect to the aluminium electrode). [中文](#)

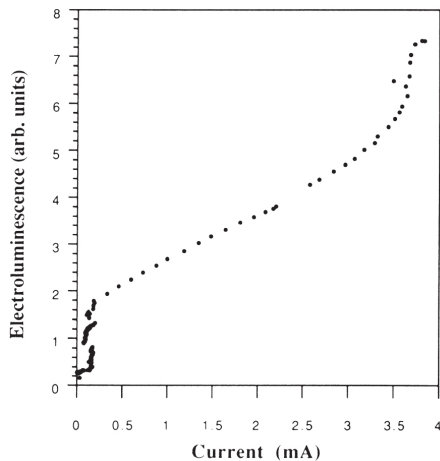


Fig. 3. Integrated light output plotted against current for the electroluminescent device giving the current–voltage characteristic in Fig. 2. [中文](#)

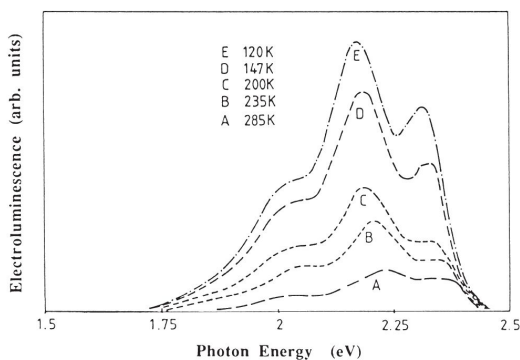


Fig. 4. Spectrally resolved output for an electroluminescent device at various temperatures. [中文](#)

The observation and characterization of electroluminescence in this conjugated polymer is of interest in the study of the fundamental excitations of this class of semiconductor. Here, the concept of self-localized charged or neutral excited states in the nonlinear response of the electronic system has been a useful one. For polymers with the symmetry of PPV, these excitations are polarons, either uncharged (as the polaron exciton) or charged (singly charged as the polaron, and doubly charged as the bipolaron)^{15,16}. We have previously assigned the photoluminescence in this polymer to radiative recombination of the singlet polaron exciton formed by intrachain excitation^{9,10} and, in view of the identical spectral emission here, we assign the

electroluminescence to the radiative decay of the same excited state. The electroluminescence is generated by recombination of the electrons and holes injected from opposite sides of the structure, however, and we must consider what the charge carriers are. We have previously noted that bipolarons, the more stable of the charged excitations in photoexcitation and chemical doping studies, are very strongly self-localized, with movement of the associated pair of energy levels deep into the semiconductor gap, to within 1 eV of each other⁹. In contrast, the movement of these levels into the gap for the neutral polaron exciton, which one-electron models predict to be the same as for the bipolaron¹⁵, is measured directly from the photoluminescence emission to be much smaller, with the levels remaining more than 2.2 eV apart. For electroluminescence then, bipolarons are very unlikely to be the charge carriers responsible for formation of polaron excitons, because their creation requires coalescence of two charge carriers, their mobilities are low and the strong self-localization of the bipolaron evident in the positions of the gap states probably does not leave sufficient energy for radiative decay at the photon energies measured here. Therefore, the charge carriers involved are probably polarons. The evidence that they can combine to form polaron excitons requires that the polaron gap states move no further into the gap than those of the polaron exciton and may account for the failure to observe the optical transitions associated with the polaron. 中文

The photoluminescence quantum yield of PPV has been estimated to be ~8%. It has been shown^{10,17} that the non-radiative processes that limit the efficiency of radiative decay as measured in photoluminescence are due to migration of the excited states to defect sites which act as non-radiative recombination centres, and also, at high intensities, to collisions between pairs of excited states. These are processes that can, in principle, be controlled through design of the polymer, and therefore there are excellent possibilities for the development of this class of materials in a range of

(347, 539-541; 1990)

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Received 21 August; accepted 18 September 1990.

References:

1. Vincent, P. S., Barlow, W. A., Hann, R. A. & Roberts, G. G. *Thin Solid Films* **94**, 476-488 (1982).
2. Tang, C. W. & VanSlyke, S. A. *Appl. Phys. Lett.* **51**, 913-915 (1987).
3. Tang, C. W., VanSlyke, S. A. & Chen, C. H. *J. appl. Phys.* **65**, 3610-3616 (1989).
4. Adachi, C., Tokito, S., Tsutsui, T. & Saito, S. *Jap. J. appl. Phys.* **27**, 59-61 (1988).
5. Adachi, C., Tsutsui, T. & Saito, S. *Appl. Phys. Lett.* **55**, 1489-1491 (1989).
6. Adachi, C., Tsutsui, T. & Saito, S. *Appl. Phys. Lett.* **56**, 799-801 (1989).
7. Nohara, M., Hasegawa, M., Hosohawa, C., Tokailin, H. & Kusomoto, T. *Chem. Lett.* 189-190 (1990).
8. Basescu, N. *et al. Nature* **327**, 403-405 (1987).
9. Friend, R. H., Bradley, D. D. C. & Townsend, P. D. *J. Phys. D* **20**, 1367-1384 (1987).
10. Bradley, D. D. C. & Friend, R. H. *J. Phys.: Condensed Matter* **1**, 3671-3678 (1989).
11. Bradley, D. D. C. *J. Phys. D* **20**, 1389-1410 (1987).
12. Murase, I., Ohnishi, T., Noguchi, T. & Hirooka, M. *Synthetic Metals* **17**, 639-644 (1987).
13. Stenger-Smith, J. D., Lenz, R. W. & Wegner, G. *Polymer* **30**, 1048-1053 (1989).
14. Bellingham, J. R., Phillips, W. A. & Adkins, C. J. *J. Phys.: Condensed Matter* **2**, 6207-6221 (1990).
15. Fesser, K., Bishop, A. R. & Campbell, D. K. *Phys. Rev. B* **27**, 4804-4825 (1983).
16. Brazovskii, S. A. & Kirova, N. N. *JEPT Lett.* **33**, 4-8 (1981).
17. Bradley, D. D. C. *et al. Springer Ser. Solid St. Sci.* **76**, 107-112 (1987).

Acknowledgements. We thank J. R. Gellingham, C. J. Adkins and W. A. Phillips for their help in preparing the indium oxide films. We thank SERC and Cambridge Research and Innovation Ltd for support.

基于共轭聚合物的发光二极管

伯勒斯等

20世纪70年代发现了导电聚合物，几种具有半导体电性能的有机聚合物被随后的研究所证实。其中之一的聚对苯撑乙烯（PPV）是由剑桥大学的理查德·弗兰德及其同事们制备的，它可被用在聚合物发光二极管（LED）中，当有电流通过时该器件发出淡黄色的光。对于传统的无机LED来说，若想得到新的发光颜色需要新的材料。但是，聚合物LED的发光波长可以通过对聚合物骨架进行化学修饰来调节，器件的发射光谱覆盖整个可见光谱区，现在它们被用作商业发光显示器的原型器件。可以采用低成本的印刷工艺制作全塑料的聚合物LED，它能像纸一样卷起。 [英文](#)

共轭聚合物是有机半导体，其半导体性能与沿聚合链离域的 π 分子轨道有关。与非聚合物的有机半导体相比，共轭聚合物的主要优点是它的可加工性，能形成有用而又耐用的结构。聚合物对电激发的响应是非线性的，在共轭链上注入一个电子和一个空穴能够形成一个自局域激发态，随后它能够以辐射方式衰减，这就表明可以在电致发光器件中应用这些材料。这里我们要论述的聚对苯撑乙烯，是通过它的前驱体溶液进行加工而获得的，它被用作大面积发光二极管中的活性成分。该聚合物具有良好的结构性质，制备简单，在光谱中的绿-黄光波段有相当高的发光效率，这些优点使该聚合物能够用于发展大面积发光显示器。 [英文](#)

人们对于固态发光器件的发展保持着长久的兴趣。诸如砷化镓等直接带隙无机半导体能实现有效发光，但是将它们用于大面积显示器既不容易也不经济。基于此，已发展出基于多晶硫化锌的体系，但效率低和

可靠性较差等缺点使其不宜进行大规模生产。由于有机分子半导体普遍具有高的光致发光量子效率，长期以来，人们一直在关注利用这些有机半导体在外加强场条件下通过电荷注入而发光（电致发光）的可能性[1-7]。发光器件是通过有机层的真空升华而制成的，尽管它的发光效率很高且发光颜色选择范围很大，但是通常存在着这样的问题：升华而得到的有机薄膜的长期稳定性不够强，导致其易于发生重结晶和其他结构性变化。 [英文](#)

改善这些有机层的结构稳定性的一种方法是从分子材料转向大分子材料，而共轭聚合物就是一个好的选择，因为从原理上讲，它们不仅能提供良好的电荷传输并能为发光提供高的量子效率。对于共轭聚合物的极大兴趣一直集中于它们作为导体材料的性质上，这些性质通常是通过大量的化学掺杂来实现的[8]，而它们的发光现象极少引起人们的注意。出现这种情况的一个原因是它们中被广泛研究的聚乙炔只呈现出很弱的光致发光。但是，那些具有较宽半导体能隙并且可以制备成十分纯的形式来控制其在缺陷位处的激发态非辐射衰减的共轭聚合物，能够表现出高光致发光的量子效率。其中，聚对苯撑乙烯（PPV）能很方便地制成高质量的薄膜，并且在一个以2.2 eV为中心的带显示出很强的光致发光，刚好低于从 π 到 π^* 的带间跃迁的阈值[9,10]。 [英文](#)

我们利用一种可溶液加工的前驱体聚合物（II）合成了PPV（I），如图1所示。该前驱体聚合物制备起来很方便，是由 α,α' -二氯对二甲苯（III）通过铈盐中间产物（IV）的聚合[11-13]得到的。在碱性条件下的水/甲醇混合物中进行聚合。反应终止后，对反应混合物进行蒸馏水透析。除去溶剂，将前驱体聚合物重新溶于甲醇中。我们发现对于在适当基质上旋涂制备前驱体聚合物薄膜来说，甲醇是一种好的溶剂。经过热转化之后（典型条件是 $\geq 250^\circ\text{C}$ ，真空中持续10小时），形成的PPV薄膜（典型厚度为100 nm）是同质、致密而均匀的。此外，该薄膜坚固而无延展性，在室温下时空气中以及温度 $> 300^\circ\text{C}$ 时在真空中都是稳定的[11]。 [英文](#)

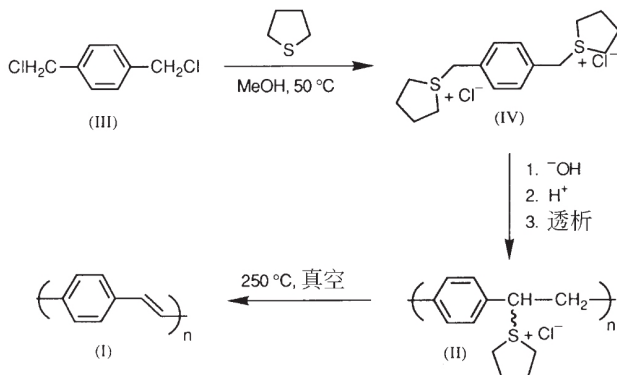


图1 . PPV的合成路线 [英文](#)

用于进行电致发光研究的器件的制备过程如下：先在适当基底（例如玻璃）上沉积一个底部电极，之后在该电极上形成PPV薄膜，最后在全覆盖的PPV薄膜上形成顶部电极。对于负的电子注入接触，我们使用低功函材料；而对于正的空穴注入接触，我们使用高功函材料，其中至少有一层对于与器件平面正交的发光必须是半透明的。为此，我们同时使用了通过离子束溅射法沉积的氧化铟^[14]和薄层的铝（典型厚度为7~15 nm）。我们发现暴露在空气中的铝能够形成薄的氧化物覆盖层，金和氧化铟都能被用作正电极材料，而铝、镁银合金和通过射频溅射所制得的非晶硅合金都适合作为负电极材料。PPV薄膜的高度稳定性使顶部接触层的沉积很容易实现，因而我们可以利用金属的热蒸镀法和氧化铟的离子束溅射法形成这种接触。 [英文](#)

图2和图3体现出以氧化铟作为底部接触且以铝作为顶部接触的器件的典型特性。大量电荷注入的阈值正好低于14 V，对应的电场强度为 $2 \times 10^6 \text{ V}\cdot\text{cm}^{-1}$ ，积分光输出随电流的变化近似为线性的。图4给出了电致发光器件在不同温度下的光谱分辨输出，其光谱与光致发光谱非常类似，在2.2 eV附近存在峰值，且清晰的声子结构^[9,10]。这些器件发出光谱中的绿-黄光波段的光，而且在正常的实验室光照条件下很容易被看到。量子效率（每注入一个电子所发出的光子数）适中，但是没有某些利用分子材料制成的结构所报道的那样高^[2-7]。我们的PPV器件的量子效率达到0.05%。我们发现这些器件中的失效模式通常都与聚合物/薄金属界面处的失效有关，这可能是因为那里的局部焦耳热引起的。 [英文](#)

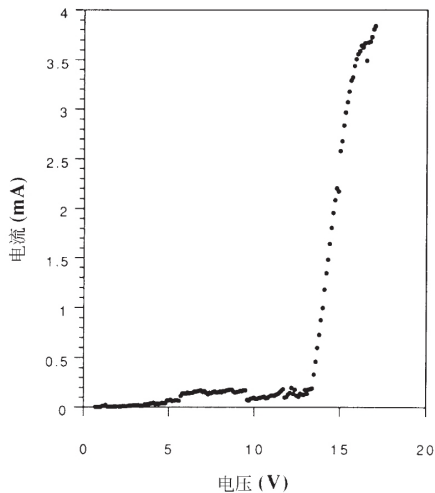


图2 . PPV薄膜电致发光器件的电流-电压特性图。PPV薄膜厚度为70 nm , 发光面积为2 mm² , 底部接触为氧化铟, 顶部接触为铝。图中显示的是正向偏置状态的曲线 (氧化铟相对于铝电极为正)。

[英文](#)

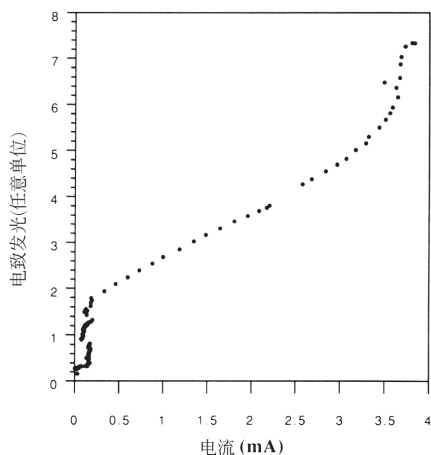


图3 . 电致发光器件的积分光输出与电流的关系图 (该器件的电流-电压特性曲线如图2所示)

[英文](#)

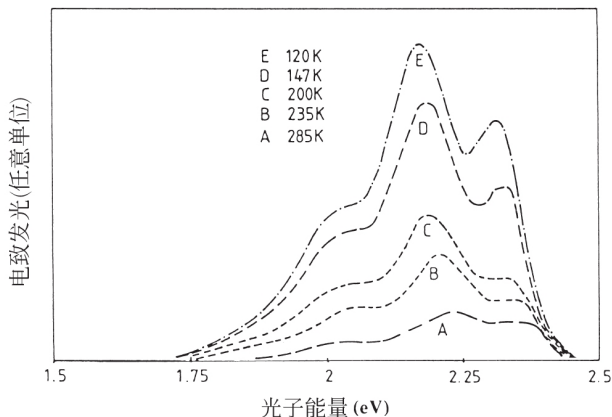


图4．电致发光器件在不同温度时的光谱分辨输出 [英文](#)

观测和描述该共轭聚合物中电致发光现象是对这类半导体基本的激发过程进行研究的兴趣所在。这里，电子体系中非线性响应的自局域带电或中性激发态概念已成为一个有用的概念。对于具有像PPV一样对称性的聚合物，这些激发是极化子，或者是不带电荷的（如极化激子）或者是带电荷的（带单个电荷的极化子，以及带两个电荷的双极化子）[15,16]。之前我们将这种聚合物中的光致发光归因于由链间激发形成的单重态极化激子的辐射复合[9,10]，而考虑到这里有同样的辐射光谱，我们将电致发光归结为相同激发态的辐射衰减。但是电致发光是由器件的相反两边注入的电子和空穴复合而产生，我们必须考虑电荷载流子是什么。之前我们已经注意到双极化子是指在光致激发与化学掺杂研究中更为稳定的带电激发，它们是极强的自局域的，伴随着双极化子能级向半导体带隙深入运动，彼此间在1 eV之内[9]。相反，对于中性极化子激子来说，根据单电子模型这些能级向能隙的移动程度与双极化子的相同[15]，由光致发光直接测得的能级移动是很小的，并且保持着超过2.2 eV的间隔。那么对于电致发光来说，双极化子不可能是使极化激子得以形成的电荷载流子，因为它们的产生需要两个电荷载流子的结合，它们的迁移率很低，而且明显出现在能隙状态所处位置的双极化子的强自局域，可能没有给在这里测得的光子能量留下足够的能量进行辐射衰减。因此，参与其中的载流子可能是极化子。关于它们能够结合而形成极化激子的这一证据，要求极化子能隙状态向能隙的运动不超过极化激子的，从而可以解释为什么无法观测到与极化子有关的光跃迁。 [英文](#)

PPV的光致发光量子效率估算约为8%。研究表明[10,17]：无辐射跃

迁过程限制光致发光中测得的辐射衰减效率，该无辐射过程是来自于激发态向作为无辐射复合中心的缺陷位点的迁移；而在高强度时，该无辐射过程还可归结为激发态对之间的碰撞。这些过程原则上是能够通过聚合物的设计来控制的，因此在一系列电致发光应用中发展这类材料具有极大的可能性。

英文

（王耀杨 翻译；于贵 朱道本 审稿）

Superconductivity at 18 K in Potassium-doped C₆₀

A. F. Hebard *et al.*

The discovery in 1990 of a method for making large quantities of the cage-like carbon molecule C₆₀ led to intensive research into its physical and chemical behaviour. Here Art Hebard and colleagues at AT&T Bell Laboratories in New Jersey report one of the most striking outcomes of that work: when doped with alkali metals, C₆₀ becomes superconducting at low temperatures, conducting electricity without resistance. The discovery followed soon after the Bell Labs team found that the doped solid had metallic conductivity. The onset temperature of superconductivity is relatively high compared to normal metals, and inspired hopes that it might be made higher still—as indeed it soon was. The finding never spawned practical applications, but was of immense theoretical interest. [中文](#)

The synthesis of macroscopic amounts of C₆₀ and C₇₀ (fullerenes)¹ has stimulated a variety of studies on their chemical and physical properties^{2,3}. We recently demonstrated that C₆₀ and C₇₀ become conductive when doped with alkali metals⁴. Here we describe low-temperature studies of potassium-doped C₆₀ both as films and bulk samples, and demonstrate that this material becomes superconducting. Superconductivity is demonstrated by microwave, resistivity and Meissner-effect measurements. Both polycrystalline

powders and thin-film samples were studied. A thin film showed a resistance transition with an onset temperature of 16 K and essentially zero resistance near 5 K. Bulk samples showed a well-defined Meissner effect and magnetic-field-dependent microwave absorption beginning at 18 K. The onset of superconductivity at 18 K is the highest yet observed for a molecular superconductor. 中文

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THE sensitivity to air of alkali-metal-doped fullerenes (A_xC_n) limits the choice of sample preparation and characterization techniques. To avoid sample degradation, we carried out reactions with the alkali metal vapour and C_{60} in sealed tubes either in high vacuum or under a partial pressure of helium. The C_{60} was purified by chromatography¹ of fullerite² and was heated at 160 °C under vacuum to remove solvents. 中文

Small amounts of the individual fullerenes (~ 0.5 mg) were placed in quartz tubes with alkali metals and sealed under vacuum. These samples were subjected to a series of heat treatments and tests for superconductivity by 9-GHz microwave-loss experiments⁵. Preliminary tests indicated that only the K-doped C_{60} showed a response consistent with a superconducting transition (Fig. 1). For this reason, together with the fact that K_xC_{60} showed the highest film conductivity¹, we focused our studies on the K-doped compound. 中文

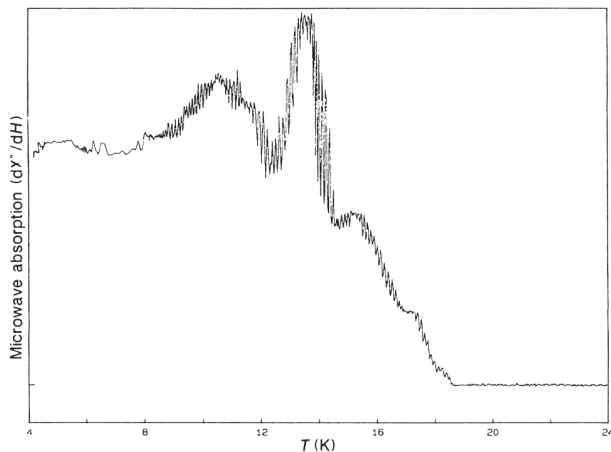


Fig. 1. Microwave loss as a function of temperature for K_xC_{60} in a static field of 20 Oe. 中

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The conductivity measurements were performed on potassium-doped films of C_{60} that were prepared in a one-piece all-glass version of the apparatus described previously⁴. This reaction vessel was sealed under a partial pressure of helium before reaction. This configuration allowed both *in situ* doping and low-temperature studies of thin films. All measurements were made in a four-terminal Van der Pauw configuration using a 3- μ A a.c. current at 17 Hz. Figure 2 shows the temperature dependence of the resistivity of a 960-Å-thick K_xC_{60} film. The film was doped with potassium until the resistivity had fallen to $5 \times 10^{-3} \Omega \text{ cm}$. The resistivity increases by a factor of two on cooling the sample to near 20 K. Below 16 K, the resistivity starts to decrease; zero resistivity ($< 10^{-4}$ of the normal state) is obtained below 5 K. The 10–90% width of the transition is 4.6 K. At 4 K we measured the lower bound to the critical current to be 40 A cm^{-2} . 中文

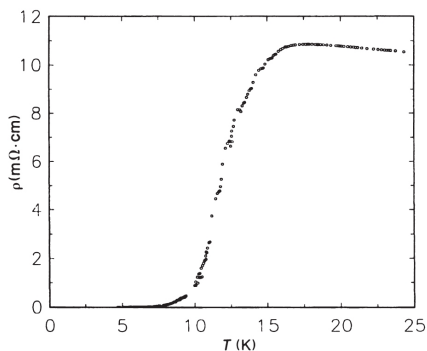


Fig. 2. Temperature dependence of the electrical resistivity of a 960-Å-thick film of K_xC_{60} .

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A bulk polycrystalline sample of nominal composition K_3C_{60} was prepared by reaction of 29.5 mg of C_{60} with 4.8 mg potassium. The amount of potassium was controlled volumetrically by using potassium-filled pyrex capillary tubing cut to size in a dry box. The reaction was run with the C_{60} in a 5-mm fused silica tube joined to a larger tube in which the potassium-containing capillary was placed. The tube was sealed after being evacuated and refilled with 10^{-2} torr of helium to serve later as a thermal-exchange gas for low-temperature measurements. With the C_{60} -containing end of the tube at room temperature, the potassium was distilled from the capillary in a furnace at 200 °C. Some reaction of the potassium with the quartz tube, visible as a dark brown discoloration, was observed at this temperature. Unreacted potassium was observed after this period. Following distillation of the potassium to the C_{60} end, the tube was shortened by sealing to about 8 cm and heated to 200 °C for 36 h. Finally, the tube was resealed to a length of about 4 cm for magnetic measurements.

中文

The temperature dependence of the d.c. magnetization of the sample with nominal composition K_3C_{60} was measured in a SQUID magnetometer (Fig. 3). On zero-field cooling the sample to 2 K, a magnetic field of 50 Oe was applied. On warming, this field is excluded by the sample to 18 K; this verifies the presence of a

superconducting phase. The bulk nature of superconductivity in the sample is demonstrated unambiguously by cooling in a field of 50 Oe. A well defined Meissner effect (flux expulsion) develops below 18 K. The shape of the magnetization curve, in particular the temperature-independent signal at low temperature, indicates good superconducting properties for this sample. Also noteworthy is the relatively narrow transition width. The magnitude of the flux exclusion for the zero-field-cooled curve corresponds to 1% volume fraction. This small fraction is possibly due to non-optimal doping or the granular nature of the sample. The large value of the Meissner effect for the field-cooled curve relative to the total exclusion, however, indicates bulk superconductivity in the electrically connected regions. 中文

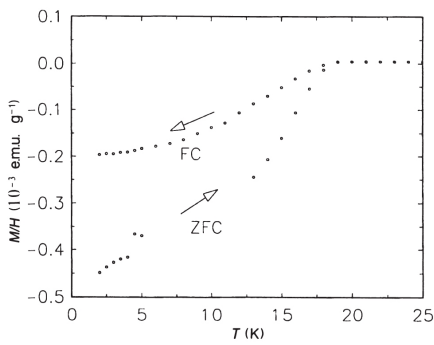


Fig. 3. Temperature dependence of the magnetization of a K_xC_{60} crystalline sample. The direction of temperature sweep in the field-cooled (FC) and the zero-field-cooled (ZFC) curves is indicated by the arrows. 中文

The universally accepted tests for superconductivity, namely a transition to zero resistance and a Meissner effect showing the expulsion of magnetic field, demonstrate unequivocally the existence of superconductivity in K_xC_{60} . The 18-K transition temperature is the highest yet reported for a molecular superconductor. This may be compared with the previously reported occurrence of superconductivity at 0.55 K in potassium-intercalated graphite⁶. We expect that optimization of composition and crystallinity will lead to further improvement in the superconducting properties. 中文

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Received 26 March; accepted 4 April 1991.

References:

1. Kroto, H. W., Heath, J. R., O'Brien, S. C., Curl, R. F. & Smalley, R. E. *Nature* **318**, 162-164 (1985).
2. Kratschmer, W., Lamb, L. D., Fostiropoulos, K. & Huffman, D. R. *Nature* **347**, 354-358 (1990).
3. Meijer, G. & Bethune, D. S. *J. Chem. Phys.* **93**, 7800-7802 (1990).
4. Haddon, R. C. *et al. Nature* **350**, 320-322 (1991).
5. Haddon, R. C., Glarum, S. H., Chichester, S. V., Ramirez, A. P. & Zimmerman, N. M. *Phys. Rev. B* **43**, 2642- 2647 (1991).
6. Hannay, N. B. *et al. Phys. Rev. Lett.* **14**, 225-226 (1965).

Acknowledgements. We thank G. Dabbagh, S. J. Duclos, R. H. Eick, A. T. Fiory, R. M. Fleming, M. L. Kaplan, K. B. Lyons, A. V. Makhija, B. Miller, A. J. Muller, K. Raghavachari, J. M. Rosamilia, L. F. Schneemeyer, F. A. Thiel, J. C. Tully, R. Tycko, R. B. Van Dover, J. V. Waszczak, W. L. Wilson and S. M. Zahurak for valuable contributions to this work.

掺钾的C₆₀在18 K时的超导性

赫巴德等

1990年制备大量笼状碳C₆₀分子方法的发现引起了人们对其物理和化学性质的集中研究。本文中，新泽西州的美国电话电报公司贝尔实验室的阿特·赫巴德和同事们报道了这项工作中的一个最显著的成果：当掺入碱金属时，C₆₀在低温下变成超导体，能够无阻导电。这是贝尔实验室继发现掺杂入金属的C₆₀具有金属导电性后的又一个发现。与一般的金属相比，它的超导起始温度相对较高，从而激发了人们使之更高的期望，不久，这就成为了事实。尽管此发现还未推广至实际应用中，但其引起了巨大的理论研究兴趣。 [英文](#)

宏观量的C₆₀和C₇₀（富勒烯）的合成^[1]已经激发了很多关于其化学和物理性质的研究^[2,3]。最近我们的实验表明：掺碱金属后的C₆₀和C₇₀具有导电性^[4]。本文中我们论述了针对掺钾C₆₀的薄膜样品和块状样品的低温研究，并且说明了这种材料能变得具有超导性。超导性是通过微波、电阻率和迈斯纳效应的测试来说明的。我们对多晶粉末和薄膜样品分别进行了研究。结果表明，薄膜呈现出以16 K为起始温度的电阻转变，而且在温度接近5 K时就具有实质上的零电阻。块状样品呈现出明显的迈斯纳效应，且温度达到18 K时出现了随磁场变化的微波吸收现象。到目前为止，18 K是人们所观测到的分子超导体最高的超导性起始温度值。 [英文](#)

掺碱金属的富勒烯（A_xC_n）对于空气的敏感性限制了样品的制备和表征技术的选择。为了避免样品变质，我们让碱金属蒸气和C₆₀在高真空或者是具有氦分压的密封管中进行反应。C₆₀是利用色谱法^[1]对富勒烯固体^[2]进行提纯且于160 °C在真空中加热除去溶剂而得到的。 [英](#)

将少量的单体富勒烯（约为0.5 mg）与碱金属同置于石英管中，并在真空条件下密封。将这些样品进行一系列热处理后，通过9 GHz微波损失实验进行超导性检测^[5]。初步的检测表明，只有掺钾的C₆₀表现出与超导转变相一致的反应（如图1所示）。由于这个原因，再加上K_xC₆₀显示出最高的薄膜导电性的事实^[1]，我们集中研究了掺钾的化合物。

英文

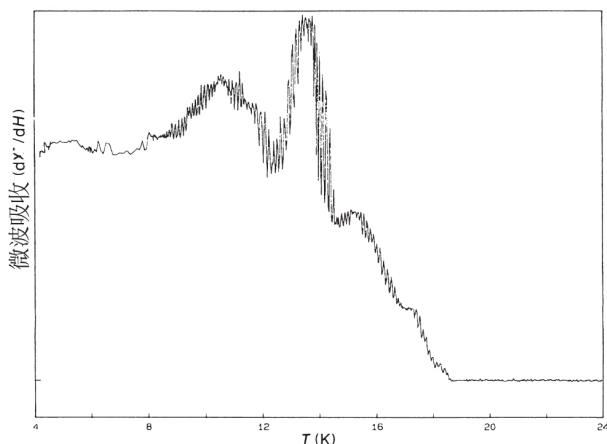


图1 . K_xC₆₀在20 Oe的静场中的微波损失关于温度的函数

英文

对掺钾的C₆₀薄膜进行导电性测试，薄膜于先前曾描述过的^[4]整体型全玻璃装置中制备。这种反应容器是在反应前具有氦分压的条件下密封的。这种构造可以同时允许原位掺杂和薄膜的低温研究。所有的测量均在四端范德堡配置中进行，条件为17 Hz频率的3 μA交流电。图2显示出厚度为960 Å的K_xC₆₀薄膜的电阻率随温度的变化关系。用钾掺杂薄膜，直到电阻率下降至 $5 \times 10^{-3} \Omega \cdot \text{cm}$ 为止。在将样品冷却至20 K左右时，电阻率增大了2倍。在温度低于16 K时，电阻率开始减小；在温度为5 K以下时得到零阻抗（ $< \text{正常态时的} 10^{-4}$ ）。电阻变化10%~90%所对应的温度间隔为4.6 K。温度为4 K时我们测得临界电流的下限值为 $40 \text{ A} \cdot \text{cm}^{-2}$ 。

英文

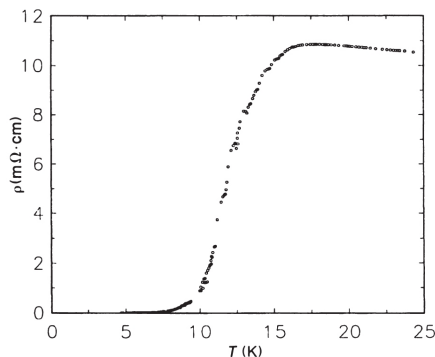


图2. 厚度为960 Å的 K_xC_{60} 薄膜电阻率随温度的变化关系

[英文](#)

标称成分为 K_3C_{60} 的块状多晶样品是通过将29.5 mg C_{60} 与4.8 mg钾反应来制备的。通过控制体积调节钾的含量，即在干燥器中把充满钾的耐热玻璃毛细管裁割至适当体积。将一个装有 C_{60} 的5 mm熔封石英管与一个放有含钾的毛细管的较大管子联结在一起，使反应得以进行。在抽真空并重新填入 10^{-2} torr的氦作为随后的低温测量中的热交换气体后，将管密封。保持含 C_{60} 的管末端处于室温状态，在温度为200 °C的炉子中将钾从毛细管中蒸馏出来。在这个温度下观察到钾与石英管的某些反应，可以看到有深褐色的褪色斑点。之后能够观察到未反应的钾。接着将钾蒸馏到 C_{60} 末端，用密封方法将管子截短至约8 cm，并将其加热到温度为200 °C，保持36小时。最后，将管子再次密封至约4 cm的长度以备磁学检测。

[英文](#)

用超导量子干涉磁强计测试了标称成分为 K_3C_{60} 的样品的直流磁化随温度变化的关系（如图3所示）。在零场中，冷却样品到2 K，再对样品加50 Oe的磁场。加热温度直到18 K时，样品都可将该场排出；这就证明了一个超导相的存在。通过在50 Oe的场冷却，已明确地说明了样品中超导性的体特征。温度低于18 K时出现了明显的迈斯纳效应（磁通排出）。磁化曲线的形状，特别是低温下与温度无关的现象，表明该样品具有良好的超导性。同样值得我们注意的是相当狭窄的转变温度范围。零场冷却曲线对应的磁通排出的大小表明超导体积比为1%。如此小的超导体积比可能是由于非理想掺杂或者是样品的粒状性质。但是，场冷却曲线的迈斯纳效应相对于总排出量的大的数值表明样品电连通区域中显著的体超导性。

[英文](#)

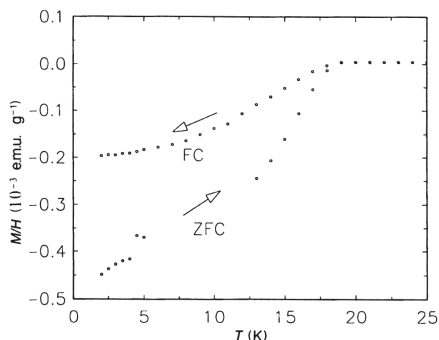


图3 . K_xC_{60} 晶体样品的磁化随温度的变化关系。箭头指出了场冷却 (FC) 与零场冷却 (ZFC) 曲线中的温度扫描方向。 [英文](#)

得到普遍认可的超导性检测，即零电阻的转变与表现为磁场排出的迈斯纳效应，明确地证明了 K_xC_{60} 中超导性的存在。18 K的转变温度是到目前为止关于分子超导体报道中最高的温度值。这可以与以前报道的插钾层的石墨在0.55 K时超导性的出现^[6]相比较。我们期望对成分与结晶度的优化能够进一步改善超导性质。 [英文](#)

(王耀杨 翻译；韩汝珊郭建栋 审稿)

Curling and Closure of Graphitic Networks under Electron-beam Irradiation

D. Ugarte

After the discovery of cage-like carbon molecules called fullerenes and tubular structures called carbon nanotubes, it was suspected that sheets of graphite-like carbon might adopt a range of nanoscale structures in a kind of molecular origami. Here Daniel Ugarte at EPFL in Lausanne, Switzerland, reports another such variant: onion-like structures comprised of nested spherical shells of carbon. Some suggested that these were like giant fullerenes, although it transpired that the shells contain many crystal defects and breaks. Carbon “onions” with hollow centres have since been used to study encapsulated materials, and intense pressures at their centres may transform graphite-like carbon into diamond. [中文](#)

The discovery¹ of buckminsterfullerene (C_{60}) and its production in macroscopic quantities² has stimulated a great deal of research. More recently, attention has turned towards other curved graphitic networks, such as the giant fullerenes (C_n , $n > 100$)^{3,4} and carbon nanotubes⁵⁻⁸. A general mechanism has been proposed⁹ in which the graphitic sheets bend in an attempt to eliminate the highly energetic dangling bonds present at the edge of the growing

structure. Here, I report the response of carbon soot particles and tubular graphitic structures to intense electron-beam irradiation in a high-resolution electron microscope; such conditions resemble a high-temperature regime, permitting a degree of structural fluidity. With increased irradiation, there is a gradual reorganization of the initial material into quasi-spherical particles composed of concentric graphitic shells. This lends weight to the nucleation scheme proposed⁹ for fullerenes, and moreover, suggests that planar graphite may not be the most stable allotrope of carbon in systems of limited size. [中文](#)

THE remarkable stability of the C_{60} molecule has been attributed to its highly symmetrical structure where the carbon atoms are arranged at the vertices of a truncated icosahedron¹. The C_{60} molecule may be viewed as a hexagonal graphitic sheet which, by incorporating pentagons, has eliminated all dangling bonds, curling to form a hollow ball (7.1 Å in diameter). For all fullerenes, the strain due to the bending of the sp^2 orbitals tends to concentrate at the vertices of the pentagons. The outstanding stability of the C_{60} molecule is due both to the fact that this is the smallest carbon cage where there are no adjacent pentagons, and to its spherical form which allows the strain to be symmetrically distributed over all atoms¹⁰. [中文](#)

In addition to C_{60} , cylindrical carbon structures have been observed⁵ in which the graphitic sheet has a helical arrangement. The natural question arises: how is it possible to generate such symmetrical, low-entropy forms from the random condensation of carbon vapour? Perhaps it is worthwhile to contemplate the ease with which these carbon hexagonal networks grow as curved or closed sheets rather than the traditionally planar ones. Chemists are conditioned to think of graphitic sheet structures as flat, where carbon atoms are bound in infinite hexagonal sheets, like chicken wire. In carbon vapour, pieces

of graphite sheet would have many dangling bonds; they would have little reason to remain flat, and the physical tendency to reach the lowest energy level available would induce the sheets to eliminate their dangling bonds by curling up¹². By heating and properly annealing pure carbon in the absence of other chemically active elements, and under conditions that favour sp^2 carbon network formation, it should be possible to synthesize curled nets and closed cages. In fact, this is the situation in arc discharges, which is the technique used at present to produce macroscopic quantities of fullerenes², metallofullerenes¹³ and graphitic tubules¹⁴. [中文](#)

Under the conditions of observation in an electron microscope, strong irradiation in some respects resembles a high-temperature regime, allowing structural fluidity; for example, amorphous carbon films usually develop slight graphitization under the electron beam. In particular, irradiation usually heats the sample by energy absorption and ruptures bonds through electron excitations. Furthermore, high-energy particles can transfer momentum to the nuclei, displacing atoms to interstitial lattice sites (“knock on”). Such conditions may be realized by electron bombardment in a high-resolution electron microscope (HREM), and consequently the evolution of a sample may be observed, even up to atomic details under favourable conditions. We must note, however, that electron-beam heating may not lead to the same result as thermal heating, because of the contribution of the excitation processes. [中文](#)

We have irradiated carbon soot in a 300-kV HREM microscope (Philips EM430 ST), using an electron dose up to 10–20 times higher than under normal operating conditions (the usual dose is 10–20 A cm⁻²). Figure 1 shows a sequence of images of a group of irradiated graphitic particles, taken at 10-minute intervals. The original soot, collected in an arc-discharge apparatus, contains mostly nanometric needles formed by coaxial graphitic tubes, with some polyhedral

graphitic particles formed by the junction of small flakes of planar graphite (Fig. 1a). All the particles are covered with a thin amorphous carbon layer. In the intermediate image of the sequence (Fig. 1b), particles now show more marked curvature and, in particular, the tubular structures are collapsing. At this stage, the amorphous carbon layer has graphitized epitaxially onto the particles. Finally (Fig. 1c), the electron annealing leads to a sample composed almost entirely of spherical particles. Detailed examination of the particles shows that they consist of an assembly of concentric spherical graphitic cages (see Fig. 2), the distance between layers agreeing with that for bulk graphite ($d_{002} = 3.34 \text{ \AA}$). The apparent disorder in the spherical shells arises as a consequence of the low electron dose necessary for taking the micrographs; under such conditions, the heating effect of the electron beam is insufficient to permit structural reorganization back to the closed-shell form. Imaging on a much shorter timescale, however, permits the observation of more complete structures. The existence of these structures has already been proposed¹⁵⁻¹⁷. 中文

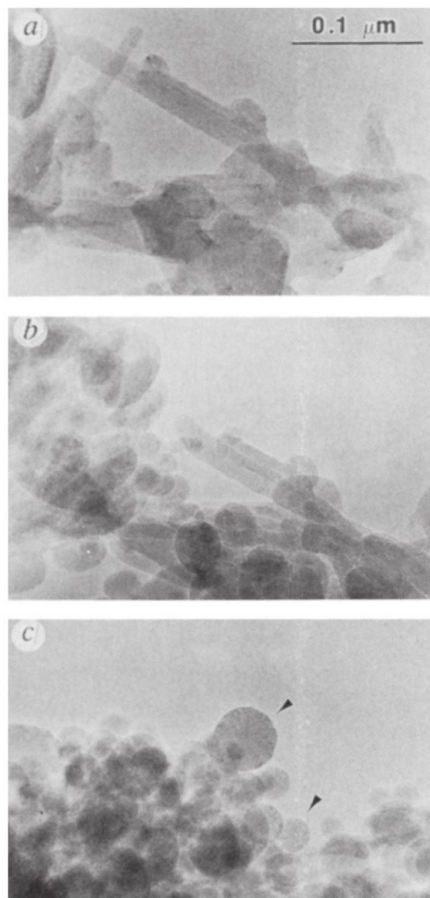


Fig. 1. Sequence of transmission electron micrographs of carbon soot subjected to strong electron beam irradiation. *a*, Original soot containing tubular or polyhedral graphitic particles; *b*, after 10 minutes of strong irradiation, there is a noticeable tendency for the particles forming the soot to become more spherical, especially the graphitic needles; *c*, after 20 minutes, the soot is nearly exclusively composed of quasi-spherical graphitic particles. Further irradiation does not produce significant observable changes in structure. 中文

The final spherical structures do not correspond to the deformation of a tube into a sphere with the same number of atoms (see scheme for single-shell particles in Fig. 3*a, b*), but rather to the formation of a multiple-shell sphere with a very small central cage (Fig. 3*c*). The reduced dimension of the final inner shell (0.6–1 nm) allows an increase in the number of shells. Following Euler's theorem, any closed hexagonal network contains exactly 12 pentagonal rings; this is the case in the tube (Fig. 3*a*, the pentagons being situated at the

hemispherical domes at the extremities of the cylinder) or in the spherical cage (Fig. 3b). The onion-like particle of Fig. 3c is formed by four closed shells; in consequence, it contains four times as many pentagons. Our results present clear experimental evidence of the spontaneous tendency of graphite to include pentagons in its hexagonal network and form curved structures. Hence, they support the dangling bond minimization scheme, proposed to explain the growth of fullerenes from carbon vapour⁹. 中文

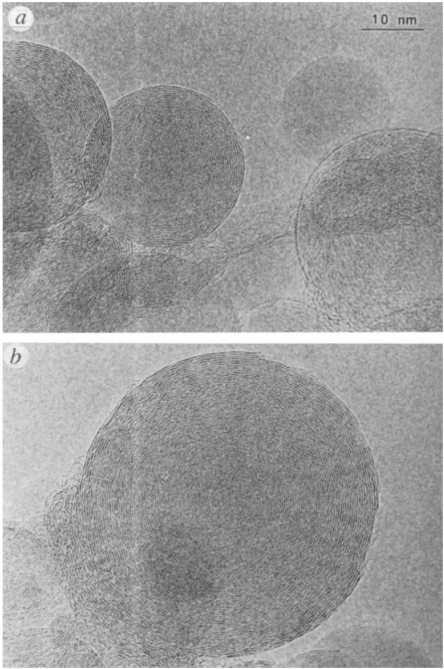


Fig. 2. Detailed structure of the graphitic particles marked with an arrow in Fig. 1c. Dark contrast rings correspond roughly to atomic positions, and the distance between rings corresponds to the (002) lattice parameter of bulk graphite. Note the remarkable sphericity of the particles. 中文

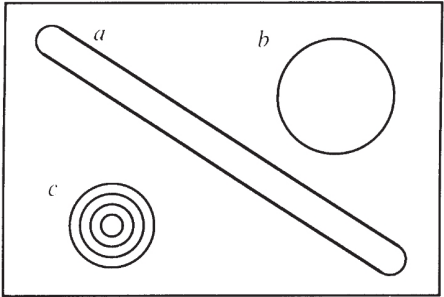


Fig. 3. Schematic representation of three-dimensional particles formed by an equal graphitic surface: *a*, cylindrical structure closed by hemispherical domes (diameter $\varnothing \approx 1$ nm and 13.7 nm long); *b*, spherical cage ($\varnothing \approx 3.74$ nm); *c*, onion-like structure formed by 4 shells ($\varnothing \approx 2.72$ nm), the central one being a C₆₀ molecule. 中文

Curved graphitic sheets can also be formed by irradiation of amorphous carbon particles (Fig. 4). The graphitic structures generated are naturally curled, and two nucleation centres are easily recognizable (marked with arrows in Fig. 4*b*), from which spherical particles will be formed. Further irradiation annealing leads to the separation of the two graphitic spheres. 中文

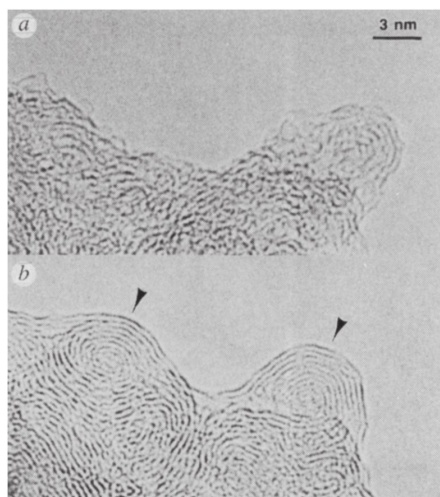


Fig. 4. Transmission electron micrographs of amorphous carbon subjected to electron irradiation. *a*, Original particle; *b*, after 10 minutes of strong irradiation, graphitization (marked with arrows) is present, and the sheets show a clear tendency to form closed cages. Further irradiation would lead to the separation of two graphitic spheres. 中文

The formation mechanism for these multiple-shell spheres is based on irradiation-stimulated graphitization, and is rather different from the accretion mechanism originally considered in laser vaporization and arc-discharge experiments, which would produce spiral multiple-shell particles⁹. 中文

The sequence shown in Fig. 1 clearly reveals that if enough energy is provided, spherical structures are favoured over tubular ones. This observation agrees with the predictions made for giant fullerenes^{18,19}

(monolayers), but van der Waals interaction between the concentric layers should be included in order to compare calculations with the present experiments. [中文](#)

The “spherical graphite” that we have observed may attain a considerable size (47 nm in diameter and ~ 70 shells for the particle shown in Fig. 2*b*). In a few cases, we have even observed spheres several micrometres in diameter, although in this range of sizes a prolonged irradiation period is required before the particles become spherical. We should not rule out the possibility that even larger (possibly macroscopic) graphitic spheres could be generated by adequate annealing of carbon; the maximum size attainable will give us information about the distortion present in the closed graphite sheets. The traditional idea that planar graphite is the most stable form of pure carbon would then have to be seriously reviewed: a flat graphite flake cannot be perfect, and includes many dangling bonds which are usually eliminated by attaching impurities (for example, hydrogen). The “spherical graphite” presented here is a pure carbon material, which has no dangling bonds, and moreover, having a spherical shape, allows a uniform distribution of the strain because of the out-of-plane geometry. Those of us accustomed to traditional planar graphite, initially surprised by the fascinating fullerenes, are now confronted with supplementary evidence that spherical carbon networks can be favoured under high temperature or strong irradiation regimes. [中文](#)

This notion also raises a point concerning the solid allotropes of carbon. When Krätschmer *et al.*² synthesized large amounts of the C₆₀ molecule for the first time, they prepared a new, third form, of solid carbon (called fullerite), which is a three-dimensional packing of C₆₀ spheres and is distinct from the two traditional crystalline carbon forms, graphite and diamond. Considering the observed tendency of graphite to form multiple-shell spheres (“onions”), of which single-

shell fullerenes are only the first member, we speculate that fullerite is the first member of a family of new solid forms of carbon that could be formed by the packing of these onion-like graphitic spheres, interacting through van der Waals forces. Further experimental work will be needed to produce and isolate multishelled graphitic spheres, but a huge family of carbon materials awaits the skill of experimentalists. 中文

(359, 707-709; 1992)

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Received 7 September; accepted 2 October 1992.

References:

1. Kroto, H. W., Heath, J. R., O'Brien, S. C., Curl, R. F. & Smalley, R. E. *Nature* **318**, 162-163 (1985).
2. Krätschmer, W., Lamb, L. D., Fostiropoulos, K. & Huffman, D. *Nature* **347**, 354-358 (1990).
3. Kroto, H. W. & McKay, K. *Nature* **331**, 328-331 (1988).
4. Lamb, L. D. *et al. Science* **255**, 1413-1416 (1992).
5. Iijima, S. *Nature* **354**, 56-58 (1991).
6. Mintimire, J. W., Dunlap, B. I. & White, C. T. *Phys. Rev. Lett.* **68**, 631-634 (1992).
7. Hamada, N., Sawada, S. & Oshiyama, A. *Phys. Rev. Lett.* **68**, 1579-1581 (1992).
8. Tanaka, K., Okahara, K., Okada, M. & Yamade, T. *Chem. Phys. Lett.* **191**, 469-472 (1992).
9. Zhang, Q. L. *et al. J. Phys. Chem.* **90**, 525-528 (1986).
10. Kroto, H. W. *Nature* **329**, 529-531 (1987).
11. Bundy, F. P. *Physica A* **156**, 169-178 (1989).
12. Robertson, D. H., Brenner, D. W. & White, C. T. *J. Phys. Chem.* **96**, 6133-6135 (1992).
13. Chai, Y. *et al. J. Phys. Chem.* **95**, 7564-7568 (1991).
14. Ebbesen, T. W. & Ajayan, P. M. *Nature* **358**, 220-222 (1992).
15. Curl, R. F. & Smalley, R. E. *Scient. Am.* **265**, 32-41 (October, 1991).
16. Iijima, S. *J. Cryst. Growth* **50**, 657-683 (1980).
17. Iijima, S. *J. Phys. Chem.* **91**, 3466-3467 (1987).
18. Adams, G. B., Sankey, O. F., Page, J. B., O'Keeffe, M. & Drabold, D. A. *Science* **256**, 1792-1795 (1992).
19. Scuseria, G. E. in *Buckminsterfullerene* (eds Billups, W. E. & Ciufolini, M. A.) (VCH, New York, in the press).

Acknowledgements. We thank H. W. Kroto and W. de Heer for discussions and comments, and D. Reinhard and B. D. Hall for critical reading of the manuscript.

石墨网络在电子束照射下的卷曲与闭合

丹尼尔·乌加特

在发现称为富勒烯的笼状碳分子和称为碳纳米管的微管结构分子后，有人估计层状石墨碳可能产生一系列折纸状纳米尺度分子。本文中，瑞士洛桑联邦理工学院的丹尼尔·乌加特报道了另一个这样的变体：由碳组成的球壳嵌套构成的洋葱状结构。一些人认为它们像巨型富勒烯，尽管人们知道其外壳中含有许多晶体缺陷和断裂。具有空心中心的“洋葱”碳已被用于封装材料的研究，在其中心的巨大压强可以把石墨状碳变成金刚石。 [英文](#)

巴克敏斯特富勒烯 (C_{60}) 的发现^[1]和它的批量制备^[2]已经激发了大量研究。最近，人们已将注意力转向其他弯曲的石墨网络，例如巨型富勒烯 ($C_n, n > 100$)^[3,4]和碳纳米管^[5-8]。通常理论认为^[9]，石墨层之所以发生弯曲，其目的在于消除出现于生长中的结构边缘的高能悬挂键。这里我要报道在高分辨率电子显微镜中的炭黑粒子和微管形石墨结构对于强电子束照射的反应；这样的条件类似于高温环境，能使结构获得一定程度的流动性。随着照射增强，存在着从初始物质向由同心石墨层组成的准球形颗粒的渐变式重组织化。这为提出^[9]的富勒烯成核理论增加了支持，而且进一步指出，平面型石墨可能不是碳在有限尺寸体系中最稳定的同素异形体。 [英文](#)

一直以来人们都将 C_{60} 分子的显著稳定性归因于其高度对称性结构，其中碳原子位于截顶二十面体的顶点处^[1]。 C_{60} 分子可以被看作是一个六角石墨层通过引入正五边形以消除所有悬挂键而卷曲成的一个空

心球（直径为 $7.1 \text{ \AA}$ ）。对于所有的富勒烯，由 sp^2 轨道弯曲而产生的应力倾向于集中在五边形的顶点处。 C_{60} 分子出色的稳定性归因于以下两个事实：它是不包含相邻五边形的最小碳笼，并且它的球状形态使应力得以对称地分布在所有原子上^[10]。 [英文](#)

除 C_{60} 之外，还观测到了圆柱形碳结构^[5]，其中石墨层具有螺旋形排布方式。由此自然产生一个问题：碳蒸气的随机凝聚是以何种方式产生出这种对称的低熵形态的呢？也许以下问题是值得思考的，即碳的六边形网络作为弯曲或闭合层的生长比起传统的平面层生长更具有便易性。化学家习惯于认为石墨层结构是平面的，碳原子被限定于无限的六边形层中，就像铁丝网一样。在碳蒸气中，石墨层碎片可以含有很多悬挂键；它们很难保持平面形，而趋向于达到可能的最低能量的物理性质将会促使层通过卷曲消除其悬挂键^[12]。在没有其他化学活性元素存在，以及有利于 sp^2 碳网络形成的条件下，通过加热纯碳并适当地退火，应该有可能合成卷曲网状和闭合笼状的物质。实际上，这就是电弧放电的情况，这是一种目前用来大量制备富勒烯^[2]、金属富勒烯^[13]和石墨微管^[14]的技术。 [英文](#)

在电子显微镜观测条件下，强烈的照射在某些方面类似于高温环境，使结构具有了流动性；例如，无定形碳薄膜在电子束照射下通常会产生轻微的石墨化。特别是，照射通常以能量吸收的方式加热样品并以电子激发的方式打断样品化学键。此外，高能粒子能将动量传递给核，使原子移动到晶格间隙位点（“撞出”）。利用高分辨率电子显微镜（HREM）中的电子轰击可以实现上述条件，同时可以观测到样品的变化过程，在有利条件下甚至可以观测到原子水平的细节。但是我们必须注意，由于激发过程的贡献，电子束加热可能不会导致与传统加热方式同样的结果。 [英文](#)

我们在一台 300 kV HREM显微镜（飞利浦EM430 ST）中照射炭黑，使用的电子束剂量超过正常操作条件下的 $10\sim 20$ 倍（通常剂量为 $10\sim 20 \text{ A}\cdot\text{cm}^{-2}$ ）。图1显示了一组经照射的石墨颗粒的图像序列，拍摄间隔为10分钟。初始炭黑是从电弧放电装置中收集到的，其中主要包含由共轴石墨管形成的纳米尺寸针状物，以及由小的平面型石墨薄片接合而形成的一些多面体石墨颗粒（图1a）。所有颗粒上都覆盖着一层薄的

无定形碳。在图像序列的中间部分（图1b）里，颗粒呈现出更为明显的曲率，特别是，微管型结构正在瓦解。在这个阶段中，无定形碳层石墨化并外延到颗粒上。最后（图1c），电子退火产生出一种几乎完全由球状颗粒组成的样品。对颗粒的详细检测表明，它们是由同心球形石墨笼的聚集体构成的（参见图2），层与层之间的距离和块状石墨中的相吻合（ $d_{002} = 3.34 \text{ \AA}$ ）。球层中明显的无序性是由拍摄显微图像所必需的低电子剂量产生的；在这样的条件下，电子束的加热效应不足以使结构重组回闭合壳层结构。不过，在短得多的时间尺度上的成像使我们得以观测更完整的结构。已有人提出这些结构是存在的^[15-17]。 [英文](#)

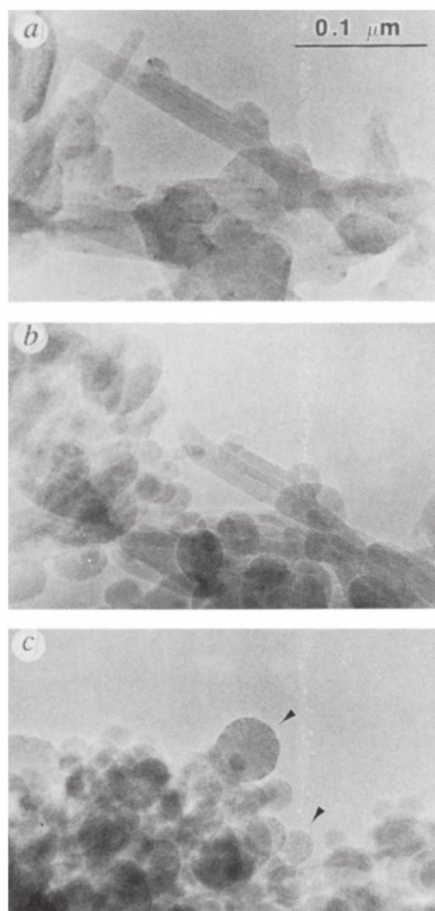


图1．炭黑遭到强电子束照射的透射电子显微图序列。*a*，含微管或多面体石墨颗粒的初始炭黑；*b*，强照射10分钟后，炭黑中的颗粒，尤其是石墨针状物中，出现了明显向球形转变的趋势；*c*，20分钟后，炭黑基本上毫无例外地由准球形石墨颗粒组成。继续照射不再产生结构上可观测的显著变化。 [英文](#)

最终的球形结构并不对应于具有相同原子数目的管到球的变形（参见图3a、b中单壳层颗粒的图解），而是形成包含一个很小的中心笼的多层球体（图3c）。最内一层尺寸的减少（0.6~1 nm）使得壳层数目增加。根据欧拉定理，任一闭合六方网络恰好包含12个五边形环；这就是管（图3a，五边形位于圆柱体末端的半球拱处）或者球形笼（图3b）的情况。图3c中的洋葱状颗粒是由四个闭合壳层形成的。因此，它包含四倍的五边形数。我们的结果为石墨在其六边形网络中包含五边形并且形成弯曲结构的自发倾向提供了清晰的实验证据。因此，它们支持了解释富勒烯能从碳蒸气中生长出来而提出的悬挂键数目最小化的理论[9]。

英文

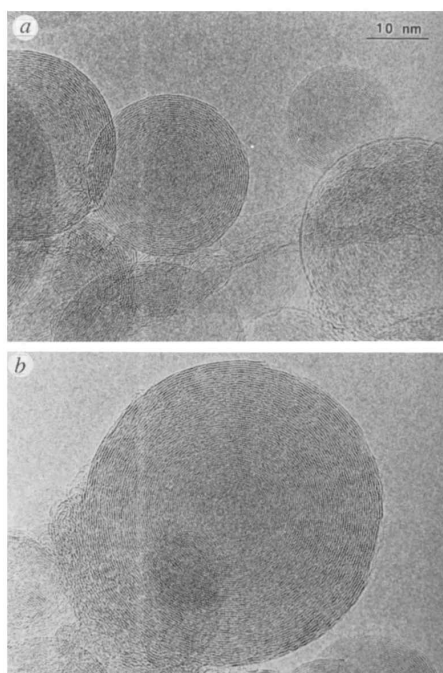


图2．图1c中箭头所指示的石墨颗粒的详细结构。暗衬度环大致上对应于原子的位置，而环之间的距离则对应于块状石墨的（002）晶格参数。注意颗粒明显为球形。

英文

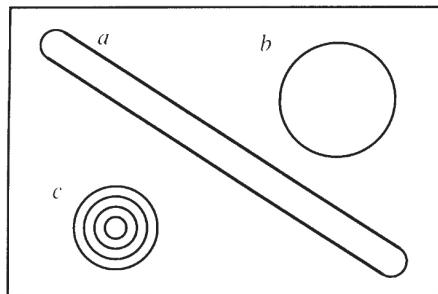


图3．由相等的石墨表面形成的三维结构示意图：*a*，用半球圆拱封口的圆柱形结构（直径 $\varnothing \approx 1$ nm，长13.7 nm）；*b*，球形笼（ $\varnothing \approx 3.74$ nm）；*c*，由四个壳层形成的洋葱状结构（ $\varnothing \approx 2.72$ nm），中心的那个是C₆₀分子。 [英文](#)

弯曲石墨层还能通过对无定形碳颗粒的照射而形成（图4）。所生成的石墨结构是天然弯曲的，并且很容易识别出两个成核中心（图4b中以箭头标出），球形颗粒就从这里开始形成。继续照射退火导致两个石墨球形颗粒的分离。 [英文](#)

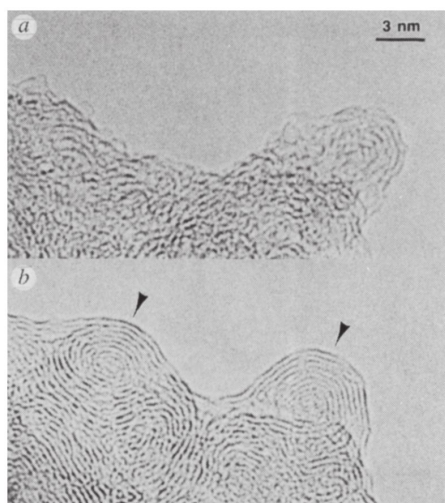


图4．接受电子束照射的无定形碳的透射电子显微图像。*a*，初始颗粒；*b*，经过10分钟强照射后，出现石墨化（用箭头标出），层呈现出清晰的形成闭合笼的倾向。继续照射会导致两个石墨球体的分离。 [英文](#)

这些多壳层球体的形成机制是基于照射激发石墨化的原理，并且与最初在激光气化和电弧放电实验中所考虑的堆积机制有很大不同，后者会产生出螺旋形多壳层颗粒^[9]。 [英文](#)

图1中显示的图像序列清楚地表明，如果提供足够的能量，球形结构比微管结构更容易形成。这一观测结果与对巨型富勒烯（单层）的预

测^[18,19]是一致的，但是要将计算结果与当前实验进行比较，则同心层之间的范德华相互作用也应包含在内。 英文

我们所观测到的“球形石墨”可能具有相当大的尺寸（图2b中显示的颗粒，直径达到47 nm，约70个壳层）。在少数情况下，我们甚至曾观测到直径达几个微米的球体，不过要达到这个范围的尺寸需要在颗粒变成球形之前延长照射时间。我们不应该排除下列可能性：更大的（可能是宏观水平的）石墨球体可以利用碳的充分退火而生产出来；所得到的最大尺寸将为我们提供关于闭合石墨层中存在的变形的信息。平面型石墨是纯碳的最稳定形态这一传统观念就不得不重新接受严肃的审视：平坦的石墨薄片不可能是完美的，其中包含很多悬挂键，它们通常是通过吸附杂质（例如氢）而得以消除的。这里所展示的“球形石墨”是一种纯净的碳物质，其中不含悬挂键，而且凭借其球形形状的非平面几何性质而使应力得到均匀分布。那些习惯于传统平面型石墨且最初为神奇的富勒烯而惊奇的研究者，现在必须面对足以证明在高温或强照射环境中更有利于球型碳网络形成的证据。 英文

这一观念还引出了一个关于碳的固态同素异形体的问题。当克雷奇默等人^[2]第一次合成大量C₆₀分子时，他们制备出了一种新型——第三种形式——的固态碳（称为富勒烯），它是C₆₀球体的三维堆积，有别于两种传统晶体形式的碳：石墨和金刚石。考虑到我们观测到的石墨形成多壳层球体（“洋葱”）的趋势——单壳层富勒烯只是第一位成员而已，我们猜测富勒烯固体是一族新的固态碳物质的第一位成员，这族固态碳物质可以通过范德华相互作用由这些洋葱状石墨球体堆积形成。要制备和分离多壳层石墨球体还需要进一步的实验研究，但是一大族碳材料正等待着实验科学家技能的发掘。 英文

（王耀杨 翻译；顾镇南 审稿）

Superconductivity above 130 K in the Hg-Ba-Ca-Cu-O System

A. Schilling *et al.*

In 1986, physicists in Switzerland discovered a ceramic material that became superconducting at temperatures below about 30 K when doped with impurities. Hitherto, many physicists suspected that superconductivity would be impossible above about 20 K, and the discovery of so-called high-temperature superconductivity kicked off a race both to explain the effect and to design new materials with even higher transition temperatures (T_c). By 1993, the record had reached 125 K; here Andreas Schilling and colleagues improve on that with a material having a T_c of 133 K. Since then the record for copper-oxide materials has been raised to 138 K. But a definitive theory to explain the phenomenon remains an outstanding problem in physics. [中文](#)

The recent discovery¹ of superconductivity below a transition temperature (T_c) of 94 K in $\text{HgBa}_2\text{CuO}_{4+\delta}$ has extended the repertoire of high- T_c superconductors containing copper oxide planes embedded in suitably structured (layered) materials. Previous experience with similar compounds containing bismuth and thallium instead of mercury suggested that even higher transition temperatures might be achieved in mercury-based compounds with more than one CuO_2 layer per unit cell. Here we provide support for this conjecture, with the discovery of

superconductivity above 130 K in a material containing $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{1+x}$ (with three CuO_2 layers per unit cell), $\text{HgBa}_2\text{CaCu}_2\text{O}_{6+x}$ (with two CuO_2 layers) and an ordered superstructure comprising a defined sequence of the unit cells of these phases. Both magnetic and resistivity measurements confirm a maximum transition temperature of ~ 133 K, distinctly higher than the previous established record value of 125–127 K observed in $\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ (refs 2, 3). [中文](#)

THE structural similarity of $\text{HgBa}_2\text{CuO}_{4+\delta}$ (Hg-1201, ref. 1) to a member of the thallium-containing family of copper oxides, $\text{TlBa}_2\text{CuO}_5$ (Tl-1201), suggests the existence of compounds with the general composition $\text{HgBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+2+\delta}$. The transition temperatures of the thallium-containing analogues, $\text{TlBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+3}$, range from < 10 K ($n=1$, ref. 4) to ~ 110 K ($n=3$, ref. 5). In this sense, transition temperatures exceeding 100 K may be expected also in the Hg–Ba–Ca–Cu–O (HBCCO) system. Although the successful synthesis of $\text{HgBa}_2\text{RCu}_2\text{O}_{6+x}$ (Hg-1212) with R being (Eu, Ca) has been reported, no superconductivity was found in that system⁶. [中文](#)

We prepared the samples following the procedure described in ref. 1 for Hg-1201. A precursor material with the nominal composition $\text{Ba}_2\text{CaCu}_2\text{O}_5$ was obtained from a well ground mixture of the respective metal nitrates, sintered at 900 °C in O_2 . After regrinding and mixing with powdered HgO , the pressed pellets were sealed in evacuated quartz tubes. These tubes were placed horizontally in tight steel containers and held at 800 °C for 5 hours. On opening the containers, we found that the quartz tubes were broken. It was not possible to reconstruct at which stage of the heating, cooling or opening procedure this happened. Some of the pellets were finally annealed for 5 hours at 300 °C in flowing oxygen. During the

preparation and the characterization of the samples, all possible measures were taken to avoid any contamination with toxic mercury or mercury-containing compounds. 中文

After annealing, the resulting black material was characterized by X-ray diffraction using the Guinier technique, by energy-dispersive X-ray spectrometry (EDS), and by selected-area electron-diffraction techniques (SAED) and high-resolution transmission electron microscopy (HRTEM). The EDX analysis showed that the samples are composites of isolated grains of BaCuO_2 ($\sim 30\%$), CuO ($\sim 30\%$), an unidentified oxide containing Hg, Ca and Cu ($\sim 15\%$), an oxide with Ca and Cu ($\sim 5\%$), and $\sim 5\%$ impurities with unspecified composition. About 15% of the total sample volume consisted of plate-like grains containing Hg, Ba, Ca and Cu. Some of these were investigated in detail by SAED and HRTEM techniques on a Phillips CM 30-ST transmission electron microscope. Both techniques showed clearly that these identified grains consist mostly of pure $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{8+x}$ (Hg-1223), disordered mixtures of Hg-1223 and Hg-1212, and a periodic stacking sequence of the latter unit cells. We found no grains or intergrowths associated with the Hg-1201 structure. As the volume fraction of the phases of interest is fairly small, we could not measure the lattice parameters precisely with the X-ray Guinier technique. Nevertheless, from the SAED patterns, we deduce the lattice constants $c=12.7(2)$ Å and $c=16.1(3)$ Å for the tetragonal Hg-1212 and Hg-1223 units, respectively, and $a=3.93(7)$ Å, valid for both types of compounds. The results for Hg-1212 are in good agreement with the values obtained in ref. 6. Figure 1 is a representative HRTEM image showing, as an example, a stacking containing both Hg-1212 and Hg-1223 layers. The stacking sequence 1223/1223/1212/1212/1223/1212 with a supercell c -axis $c \approx 86.4$ Å extends beyond 2,000 Å, thus qualifying this superstructure as a proper phase. HRTEM images as well as SAED patterns gave no evidence for the presence of HgO-double layers. 中文

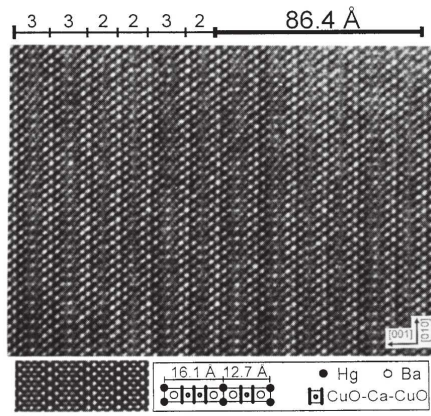


Fig. 1. HRTEM image of a grain in [100] orientation, containing layers of Hg-1212 and Hg-1223. Here, they are stacked in a periodic sequence forming a supercell with $c \approx 86.4 \text{ \AA}$ (see text). A contrast simulation ($c_s = 1.1 \text{ mm}$, $E = 300 \text{ keV}$, defocus $-870 \text{ \AA}$, specimen thickness $23 \text{ \AA}$) is inserted. The stacking sequence in terms of the number of Cu–O planes and an enlarged schematic drawing of the involved unit cells are included. 中文

We measured the magnetic susceptibility of the specimens using a SQUID-magnetometer (Quantum Design). Figure 2 shows the result obtained for an oxygen-annealed sample. In an external field $H = 27 \text{ Oe}$, the zero-field cooling susceptibility (ZFC) amounts to $\sim 100\%$ of $1/4\pi$ at temperature $T = 6 \text{ K}$, indicating complete magnetic screening. For this estimate, we assumed an average density $\rho \approx 6 \text{ g cm}^{-3}$. The field-cooling (FC) susceptibility reaches $\sim 10\%$ of the maximum possible value. This value represents a lower-bound value for the true superconducting volume fraction in the sample, indicating the bulk nature of superconductivity. The onset temperature of diamagnetism is $T_c \approx 133.5 \text{ K}$, seen both in FC and ZFC experiments (see Fig. 2, inset). The FC susceptibility reaches $\sim 60\%$ of its full low-temperature value at 125 K , strongly indicating that the phase with $T_c \approx 133.5 \text{ K}$ dominates all other superconducting phases. In the ZFC curves, additional features are seen at 126 K and 112 K , which we ascribe to different superconducting phases with lower transition temperatures.

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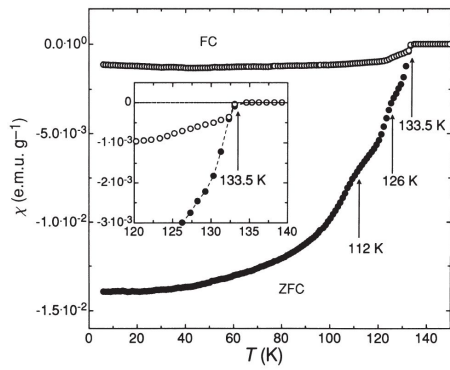


Fig. 2. Zero-field cooling (ZFC) and field cooling (FC) susceptibilities $\chi(T)$ of one of the investigated oxygen-annealed HBCCO samples, measured in $H=27$ Oe. The ZFC curve indicates the presence of several different superconducting phases. 中文

The resistivity R as a function of temperature T of an annealed sample is shown in Fig. 3. At $T \approx 132.5$ K, $R(T)$ drops sharply with a maximum in the differential dR/dT , and reaches zero at $T=95$ K within the resolution of the four-probe a.c.-resistance bridge used. This temperature is still considerably higher than the zero-resistance temperature $T \approx 35$ K, reported for Hg-1201 (ref. 1) The final oxygen treatment was very effective in increasing the critical temperature; the as-sintered samples showed a maximum T_c of only ~ 117 K. 中文

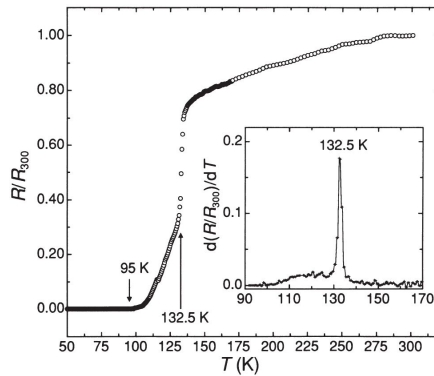


Fig. 3. Resistivity $R(T)$ of an annealed HBCCO specimen, normalized with respect to the resistance value $R(300) \approx 0.10$ Ω . The inset displays the temperature derivative dR/dT to show the maximum resistivity drop at $T \approx 132.5$ K. Zero resistance is attained at $T=95$ K.

中文

At present we cannot relate the different superconducting phases to crystallographic phases. There is no unambiguous proof that the

occurrence of superconductivity in our samples stems from the $\text{HgBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+2+\delta}$ phases. In analogy with the thallium- and bismuth-based copper oxides⁵, however, we suggest that in the HBCCO system T_c also increases with the number of Cu–O planes per unit cell, and conclude that Hg-1223 is responsible for superconductivity at ~ 133 K. This would be consistent with the large relative superconducting volume fraction at 125 K, in view of the dominance of Hg-1223 observed in the grains investigated microscopically. [中文](#)

(363, 56-58; 1993)

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Received 14 April; accepted 15 April 1993.

References:

1. Putlin, S. N., Antipov, E. V., Chmaissem, O. & Marezio, M. *Nature* **362**, 226-228 (1993).
2. Kaneko, T., Yamauchi, H. & Tanaka, S. *Physica C* **178**, 377-382 (1991).
3. Parkin, S. S. P. *et al. Phys. Rev. Lett.* **60**, 2539-2542 (1988).
4. Gopalakrishnan, I. K., Yakhmi, J. V. & Iyer, R. M. *Physica C* **175**, 183-186 (1991).
5. Parkin, S. S. P. *et al. Phys. Rev. Lett.* **61**, 750-753 (1988).
6. Putlin, S. N., Bryntse, I. & Antipov, E. V. *Mat. Res. Bull.* **26**, 1299-1307 (1991).

Acknowledgements. We thank S. Ritsch for his help in the structural characterization. This work was supported in part by the Schweizerische Nationalfonds zur Förderung der wissenschaftlichen Forschung.

Hg-Ba-Ca-Cu-O体系在130 K以上时的超导性

席林等

1986年，两位瑞士物理学家发现了一种氧化物陶瓷材料，在温度低于约30 K时具有超导性。此前，许多物理学家们推测超导温度不可能高于20 K，而高温超导的发现开启了理论解释和实验探索具有更高转变温度 (T_c) 的新超导材料的竞赛。在1993年以前， T_c 记录值已达到125 K。本文中的安德烈亚斯·席林及其同事们发现一种 T_c 为133 K的新型超导材料。从此，铜氧化物材料的 T_c 温度记录提升至138 K。但是目前在物理上并没有一种明确的理论解释。 [英文](#)

最近对于 $\text{HgBa}_2\text{CuO}_{4+\delta}$ 在低于94 K转变温度 (T_c) 的超导性的发现^[1]，进而扩大到对适当（层状）结构中含有铜氧面的高 T_c 超导体的研究。以前用含铋和铊而不是汞的类似复合物所进行的实验表明，每个单胞中 CuO_2 层多于一个的汞基复合物有可能达到更高的转变温度。本文对这一猜测提供了支持：因为发现高于130 K的超导性存在于含有 $\text{HgBa}_2\text{Ca}_2\text{Cu}_3\text{O}_{1+x}$ （每个单胞中有三个 CuO_2 层）、 $\text{HgBa}_2\text{CaCu}_2\text{O}_{6+x}$ （含两个 CuO_2 层）的材料中，而且这两相的单胞以确定的序列形成有序的超结构。磁性和电阻测量都确认最大转变温度约为133 K，明显高于过去在 $\text{Tl}_2\text{Ba}_2\text{Ca}_2\text{Cu}_3\text{O}_{10}$ （参考文献2，3）中观测到的记录值125~127 K。 [英文](#)

$\text{HgBa}_2\text{CuO}_{4+\delta}$ （Hg-1201，参考文献1）与铊系铜氧化物，如 $\text{TlBa}_2\text{CuO}_5$ （Tl-1201），在结构上的相似性暗示着具有组成通式为 $\text{HgBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+2+\delta}$ 的化合物的存在。含铊化合物 $\text{TlBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n}$

+₃的转变温度范围在小于10 K ($n=1$, 参考文献4) 至约110 K ($n=3$, 参考文献5) 之间。从这种意义上来看, 我们可以预期Hg-Ba-Ca-Cu-O (HBCCO) 体系也会有超过100 K的转变温度。尽管已有HgBa₂RCu₂O_{6+x} (Hg-1212) (R为Eu, Ca) 的成功合成的报道, 但却没有在该体系中发现超导性[6]。 [英文](#)

我们根据参考文献1中所描述的制备Hg - 1201的过程制备了样品。将每种金属的硝酸盐的混合物充分研磨, 在900 °C于氧气中烧结, 得到一种具有标称成分Ba₂CaCu₂O₅的前驱物。烧结物与HgO粉末混合并重新研磨后, 压制成片并密封于抽成真空的石英管中。再将石英管水平地放置于钢质密闭容器中, 于温度为800 °C下保持5小时。打开容器时, 我们发现石英管已经破裂。我们无法推想破裂发生在加热、冷却或开启过程中的哪个阶段。最后将部分的样片在流动的氧气中于300 °C退火5小时。在样品的制备和表征过程中, 采用了各种可能的措施以避免有毒的汞或含汞化合物的污染。 [英文](#)

在退火之后, 将所得黑色物质采用吉尼耶技术的X射线衍射、能量色散X射线光谱(EDS)、选区电子衍射技术(SAED)和高分辨透射电子显微镜(HRTEM)进行表征。EDX分析表明, 样品是由下列物质的分离的颗粒所组成: 包括BaCuO₂ (约30%)、CuO (约30%)、一种含Hg、Ca和Cu组成不明的氧化物(约15%)、一种含Ca和Cu的氧化物(约5%)和约5%含未确定成分的杂质。样品总体积中约15%的部分是由含Hg、Ba、Ca和Cu的片状颗粒组成。我们对其中某些区域用菲利普斯CM 30-ST透射电子显微镜进行了SAED和HRTEM技术的详细研究。两种技术都清楚地表明, 上述所检验的颗粒主要包含纯的HgBa₂Ca₂Cu₃O_{8+x} (Hg-1223)、无序的Hg-1223与Hg-1212的混合物, 以及这两种单胞的周期性堆垛序列。我们没有发现与Hg-1201结构有关的颗粒或共生物。由于有意义的相只占相当小的体积分数, 我们未能用X射线吉尼耶技术精确地测量其晶格参数。尽管如此, 根据SAED图像, 我们推测四方晶系Hg-1212和Hg-1223的晶格常数分别为 $c=12.7(2) \text{ \AA}$ 和 $c=16.1(3) \text{ \AA}$, 以及对两种化合物都有效的 $a=3.93(7) \text{ \AA}$ 。对Hg-1212的观测结果与参考文献6所得到的数值非常吻合。图1是典型的HRTEM图像, 例如, 它显示的堆垛同时含有Hg-

1212和Hg-1223层。具有超晶格 c 轴 $c \approx 86.4$ Å按照
 1223/1223/1212/1212/1223/1212堆垛序列延展到超过2,000 Å，因
 而可将这种超结构视为本征相。HRTEM和SAED图像都未能证明有HgO
 双层的存在。 英文

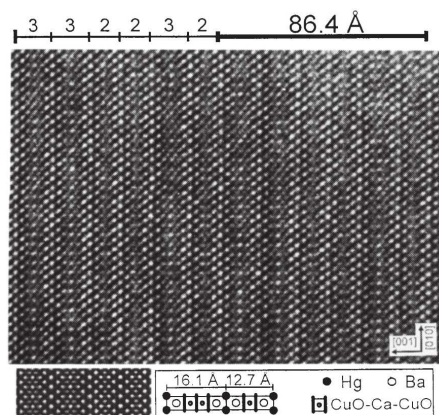


图1．晶粒在[100]取向上的HRTEM图像，包含Hg-1212和Hg-1223层。按照周期顺序，它们堆垛形成 $c \approx 86.4$ Å（见正文）的超晶格。插图是一个衬度模拟（ $c_s = 1.1$ mm， $E = 300$ keV，散焦-870 Å，样品厚度23 Å）。右下方表示的是以Cu-O平面层的数目表示的堆垛序列和有关晶胞的放大示意图。 英文

我们使用一台超导量子干涉磁强计（量子设计）测量了样品的磁化率。图2显示的是有氧退火样品所测得的结果。在 $H = 27$ Oe的外场下，零场冷却磁化率（ZFC）相当于温度 $T = 6$ K时达到 $1/4\pi$ 的100%左右，显示出完全的磁屏蔽。基于这一点估计，我们假定其平均密度 ρ 约为 $6 \text{ g} \cdot \text{cm}^{-3}$ 。场冷却（FC）磁化率达到最大可能值的10%左右。这个数值相当于样品中真正超导部分的体积分数的下限值，表明了体超导特性。抗磁性的起始温度 T_c 约为133.5 K，在FC和ZFC实验中均是如此（见图2中插图）。FC磁化率在温度为125 K时达到其完全低温数值的60%左右，强烈地表明 $T_c \approx 133.5$ K的相比其他所有超导相都有优势。在ZFC曲线中，在温度为126 K和112 K处可以看到其他的特征，我们将其归结为另外的具有较低转变温度的不同超导相所引起的。 英文

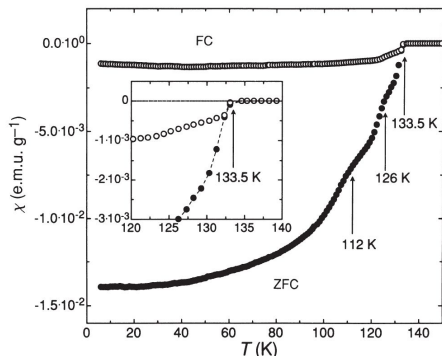


图2．一份有氧退火的HBCCO研究样品的零场冷却（ZFC）和场冷却（FC）磁化率 $\chi(T)$ ，在 $H=27$ Oe中测得。ZFC曲线指出若干个不同超导相的存在。 [英文](#)

图3中显示了经退火处理样品的电阻 R 作为温度 T 的函数的变化。在温度 T 约为132.5 K处， $R(T)$ 急剧下降，其微分值 dR/dT 达到最大值，并且在四电极交流电阻桥的分辨率下观测到在温度 T 为95 K处达到零电阻。这个温度比起对于Hg-1201所报道的（参考文献1）零电阻温度 T 约35 K还是高出很多。最后的氧处理对于提高临界温度非常有效；那些原始烧结的样品具有的最高温度 T_c 只有约117 K。 [英文](#)

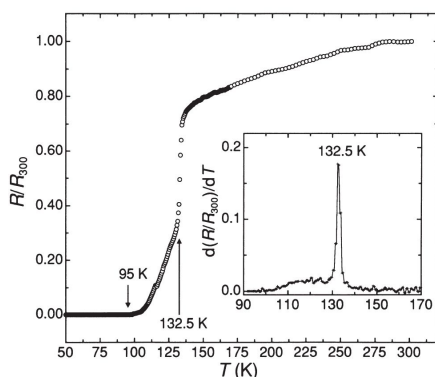


图3．一份经退火处理的HBCCO样品的电阻 $R(T)$ ，以阻值 $R(300) \approx 0.10 \Omega$ 为标准。插图显示了温度的导数 dR/dT 以表明 $T \approx 132.5$ K处的最大电阻降。在 $T=95$ K时得到零电阻。 [英文](#)

目前我们还无法将不同的超导相与各个晶相一一对应起来。还没有明确的证据表明我们的样品的超导性是源于 $\text{HgBa}_2\text{Ca}_{n-1}\text{Cu}_n\text{O}_{2n+2+\delta}$ 相。不过，与铋基和铋基铜的氧化物^[5]类比，我们认为，HBCCO体系的 T_c 也会随着每个单胞中Cu-O平面数目的增加而升高，并断言Hg-1223是温度约为133 K时超导性产生的原因。考虑到用显微镜研究颗粒时所观测到的Hg-1223占优势，这与125 K时大的相对超导体积分是一致的。

(王耀杨 翻译；韩汝珊 郭建栋 审稿)

Experimental Quantum Teleportation

D. Bouwmeester *et al.*

Exploitation of the principles of quantum physics to manipulate information in new ways is giving rise to the discipline of quantum information technology, which promises superfast quantum computers and secure quantum cryptography. One exotic possibility allowed by quantum physics is the instantaneous transfer of a quantum state over large distances: quantum teleportation. This is enabled by using the phenomenon of entanglement, in which the states of two or more quantum particles are interdependent. Here Anton Zeilinger and colleagues at the University of Innsbruck report the first experimental demonstration of quantum teleportation, in which the polarization state of one photon is transferred to another entangled photon some distance away. Realized within the laboratory here, quantum teleportation has now been achieved over more than a hundred kilometres. [中文](#)

Quantum teleportation—the transmission and reconstruction over arbitrary distances of the state of a quantum system—is demonstrated experimentally. During teleportation, an initial photon which carries the polarization that is to be transferred and one of a pair of entangled photons are subjected to a measurement such that the second photon of the entangled pair acquires the

polarization of the initial photon. This latter photon can be arbitrarily far away from the initial one. Quantum teleportation will be a critical ingredient for quantum computation networks. [中文](#)

THE dream of teleportation is to be able to travel by simply reappearing at some distant location. An object to be teleported can be fully characterized by its properties, which in classical physics can be determined by measurement. To make a copy of that object at a distant location one does not need the original parts and pieces—all that is needed is to send the scanned information so that it can be used for reconstructing the object. But how precisely can this be a true copy of the original? What if these parts and pieces are electrons, atoms and molecules? What happens to their individual quantum properties, which according to the Heisenberg's uncertainty principle cannot be measured with arbitrary precision? [中文](#)

Bennett *et al.*¹ have suggested that it is possible to transfer the quantum state of a particle onto another particle—the process of quantum teleportation—provided one does not get any information about the state in the course of this transformation. This requirement can be fulfilled by using entanglement, the essential feature of quantum mechanics². It describes correlations between quantum systems much stronger than any classical correlation could be. [中文](#)

The possibility of transferring quantum information is one of the cornerstones of the emerging field of quantum communication and quantum computation³. Although there is fast progress in the theoretical description of quantum information processing, the difficulties in handling quantum systems have not allowed an equal advance in the experimental realization of the new proposals. Besides the promising developments of quantum cryptography⁴ (the first provably secure way to send secret messages), we have only recently

succeeded in demonstrating the possibility of quantum dense coding⁵, a way to quantum mechanically enhance data compression. The main reason for this slow experimental progress is that, although there exist methods to produce pairs of entangled photons⁶, entanglement has been demonstrated for atoms only very recently⁷ and it has not been possible thus far to produce entangled states of more than two quanta.

[中文](#)

Here we report the first experimental verification of quantum teleportation. By producing pairs of entangled photons by the process of parametric down-conversion and using two-photon interferometry for analysing entanglement, we could transfer a quantum property (in our case the polarization state) from one photon to another. The methods developed for this experiment will be of great importance both for exploring the field of quantum communication and for future experiments on the foundations of quantum mechanics.

[中文](#)

The Problem

To make the problem of transferring quantum information clearer, suppose that Alice has some particle in a certain quantum state $|\psi\rangle$ and she wants Bob, at a distant location, to have a particle in that state. There is certainly the possibility of sending Bob the particle directly. But suppose that the communication channel between Alice and Bob is not good enough to preserve the necessary quantum coherence or suppose that this would take too much time, which could easily be the case if $|\psi\rangle$ is the state of a more complicated or massive object. Then, what strategy can Alice and Bob pursue?

[中文](#)

As mentioned above, no measurement that Alice can perform on $|\psi\rangle$ will be sufficient for Bob to reconstruct the state because the state of a quantum system cannot be fully determined by measurements. Quantum systems are so evasive because they can be in a superposition of several states at the same time. A measurement on

the quantum system will force it into only one of these states—this is often referred to as the projection postulate. We can illustrate this important quantum feature by taking a single photon, which can be horizontally or vertically polarized, indicated by the states $|\leftrightarrow\rangle$ and $|\updownarrow\rangle$. It can even be polarized in the general superposition of these two states

$$|\psi\rangle = \alpha |\leftrightarrow\rangle + \beta |\updownarrow\rangle \quad (1)$$

where α and β are two complex numbers satisfying $|\alpha|^2 + |\beta|^2 = 1$. To place this example in a more general setting we can replace the states $|\leftrightarrow\rangle$ and $|\updownarrow\rangle$ in equation (1) by $|0\rangle$ and $|1\rangle$, which refer to the states of any two-state quantum system. Superpositions of $|0\rangle$ and $|1\rangle$ are called qubits to signify the new possibilities introduced by quantum physics into information science⁸. [中文](#)

If a photon in state $|\psi\rangle$ passes through a polarizing beam splitter—a device that reflects (transmits) horizontally (vertically) polarized photons—it will be found in the reflected (transmitted) beam with probability $|\alpha|^2$ ($|\beta|^2$). Then the general state $|\psi\rangle$ has been projected either onto $|\leftrightarrow\rangle$ or onto $|\updownarrow\rangle$ by the action of the measurement. We conclude that the rules of quantum mechanics, in particular the projection postulate, make it impossible for Alice to perform a measurement on $|\psi\rangle$ by which she would obtain all the information necessary to reconstruct the state. [中文](#)

The Concept of Quantum Teleportation

Although the projection postulate in quantum mechanics seems to bring Alice's attempts to provide Bob with the state $|\psi\rangle$ to a halt, it was realised by Bennett *et al.*¹ that precisely this projection postulate enables teleportation of $|\psi\rangle$ from Alice to Bob. During teleportation Alice will destroy the quantum state at hand while Bob receives the quantum state, with neither Alice nor Bob obtaining information

about the state $|\psi\rangle$. A key role in the teleportation scheme is played by an entangled ancillary pair of particles which will be initially shared by Alice and Bob. [中文](#)

Suppose particle 1 which Alice wants to teleport is in the initial state $|\psi\rangle_1 = \alpha |\leftrightarrow\rangle_1 + \beta |\downarrow\rangle_1$ (Fig. 1a), and the entangled pair of particles 2 and 3 shared by Alice and Bob is in the state:

$$|\psi^-\rangle_{23} = \frac{1}{\sqrt{2}} (|\leftrightarrow\rangle_2 |\downarrow\rangle_3 - |\downarrow\rangle_2 |\leftrightarrow\rangle_3) \tag{2}$$

That entangled pair is a single quantum system in an equal superposition of the states $|\leftrightarrow\rangle_2 |\downarrow\rangle_3$ and $|\downarrow\rangle_2 |\leftrightarrow\rangle_3$. The entangled state contains no information on the individual particles; it only indicates that the two particles will be in opposite states. The important property of an entangled pair is that as soon as a measurement on one of the particles projects it, say, onto $|\leftrightarrow\rangle$ the state of the other one is determined to be $|\downarrow\rangle$, and vice versa. How could a measurement on one of the particles instantaneously influence the state of the other particle, which can be arbitrarily far away? Einstein, among many other distinguished physicists, could simply not accept this “spooky action at a distance”. But this property of entangled states has now been demonstrated by numerous experiments (for reviews, see refs 9, 10). [中文](#)

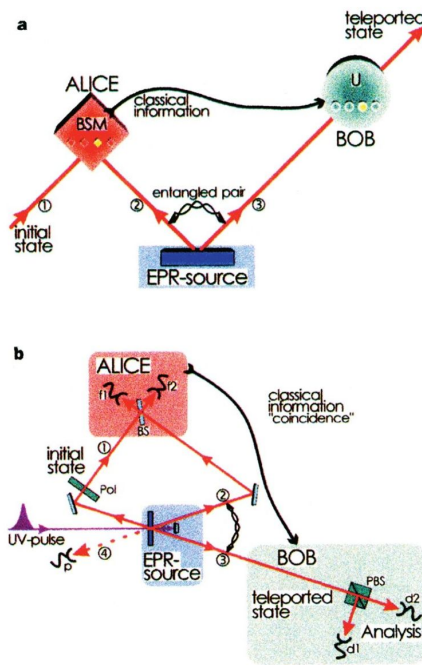


Fig. 1. Scheme showing principles involved in quantum teleportation (a) and the experimental set-up (b). **a**, Alice has a quantum system, particle 1, in an initial state which she wants to teleport to Bob. Alice and Bob also share an ancillary entangled pair of particles 2 and 3 emitted by an Einstein–Podolsky–Rosen (EPR) source. Alice then performs a joint Bell-state measurement (BSM) on the initial particle and one of the ancillaries, projecting them also onto an entangled state. After she has sent the result of her measurement as classical information to Bob, he can perform a unitary transformation (U) on the other ancillary particle resulting in it being in the state of the original particle. **b**, A pulse of ultraviolet radiation passing through a nonlinear crystal creates the ancillary pair of photons 2 and 3. After retroreflection during its second passage through the crystal the ultraviolet pulse creates another pair of photons, one of which will be prepared in the initial state of photon 1 to be teleported, the other one serving as a trigger indicating that a photon to be teleported is under way. Alice then looks for coincidences after a beam splitter BS where the initial photon and one of the ancillaries are superposed. Bob, after receiving the classical information that Alice obtained a coincidence count in detectors f1 and f2 identifying the $|\psi^-\rangle_{12}$ Bell state, knows that his photon 3 is in the initial state of photon 1 which he then can check using polarization analysis with the polarizing beam splitter PBS and the detectors d1 and d2. The detector p provides the information that photon 1 is under way. 中文

The teleportation scheme works as follows. Alice has the particle 1 in the initial state $|\psi\rangle_1$ and particle 2. Particle 2 is entangled with particle 3 in the hands of Bob. The essential point is to perform a specific measurement on particles 1 and 2 which projects them onto

the entangled state:

$$|\psi^-\rangle_{12} = \frac{1}{\sqrt{2}} (|\leftrightarrow\rangle_1 |\uparrow\downarrow\rangle_2 - |\uparrow\downarrow\rangle_1 |\leftrightarrow\rangle_2) \quad (3)$$

This is only one of four possible maximally entangled states into which any state of two particles can be decomposed. The projection of an arbitrary state of two particles onto the basis of the four states is called a Bell-state measurement. The state given in equation (3) distinguishes itself from the three other maximally entangled states by the fact that it changes sign upon interchanging particle 1 and particle 2. This unique antisymmetric feature of $|\psi^-\rangle_{12}$ will play an important role in the experimental identification, that is, in measurements of this state. [中文](#)

Quantum physics predicts¹ that once particles 1 and 2 are projected into $|\psi^-\rangle_{12}$, particle 3 is instantaneously projected into the initial state of particle 1. The reason for this is as follows. Because we observe particles 1 and 2 in the state $|\psi^-\rangle_{12}$ we know that whatever the state of particle 1 is, particle 2 must be in the opposite state, that is, in the state orthogonal to the state of particle 1. But we had initially prepared particle 2 and 3 in the state $|\psi^-\rangle_{23}$, which means that particle 2 is also orthogonal to particle 3. This is only possible if particle 3 is in the same state as particle 1 was initially. The final state of particle 3 is therefore:

$$|\psi\rangle_3 = \alpha|\leftrightarrow\rangle_3 + \beta|\uparrow\downarrow\rangle_3 \quad (4)$$

We note that during the Bell-state measurement particle 1 loses its identity because it becomes entangled with particle 2. Therefore the state $|\psi\rangle_1$ is destroyed on Alice's side during teleportation. [中文](#)

This result (equation (4)) deserves some further comments. The transfer of quantum information from particle 1 to particle 3 can happen over arbitrary distances, hence the name teleportation. Experimentally, quantum entanglement has been shown¹¹ to survive

over distances of the order of 10 km. We note that in the teleportation scheme it is not necessary for Alice to know where Bob is. Furthermore, the initial state of particle 1 can be completely unknown not only to Alice but to anyone. It could even be quantum mechanically completely undefined at the time the Bell-state measurement takes place. This is the case when, as already remarked by Bennett *et al.*¹, particle 1 itself is a member of an entangled pair and therefore has no well-defined properties on its own. This ultimately leads to entanglement swapping^{12,13}. 中文

It is also important to notice that the Bell-state measurement does not reveal any information on the properties of any of the particles. This is the very reason why quantum teleportation using coherent two-particle superpositions works, while any measurement on one-particle superpositions would fail. The fact that no information whatsoever is gained on either particle is also the reason why quantum teleportation escapes the verdict of the no-cloning theorem¹⁴. After successful teleportation particle 1 is not available in its original state any more, and therefore particle 3 is not a clone but is really the result of teleportation. 中文

A complete Bell-state measurement can not only give the result that the two particles 1 and 2 are in the antisymmetric state, but with equal probabilities of 25% we could find them in any one of the three other entangled states. When this happens, particle 3 is left in one of three different states. It can then be brought by Bob into the original state of particle 1 by an accordingly chosen transformation, independent of the state of particle 1, after receiving via a classical communication channel the information on which of the Bell-state results was obtained by Alice. Yet we note, with emphasis, that even if we chose to identify only one of the four Bell states as discussed above, teleportation is successfully achieved, albeit only in a quarter of the cases. 中文

Experimental Realization

Teleportation necessitates both production and measurement of entangled states; these are the two most challenging tasks for any experimental realization. Thus far there are only a few experimental techniques by which one can prepare entangled states, and there exist no experimentally realized procedures to identify all four Bell states for any kind of quantum system. However, entangled pairs of photons can readily be generated and they can be projected onto at least two of the four Bell states. [中文](#)

We produced the entangled photons 2 and 3 by parametric down-conversion. In this technique, inside a nonlinear crystal, an incoming pump photon can decay spontaneously into two photons which, in the case of type II parametric down-conversion, are in the state given by equation (2) (Fig. 2)⁶. [中文](#)

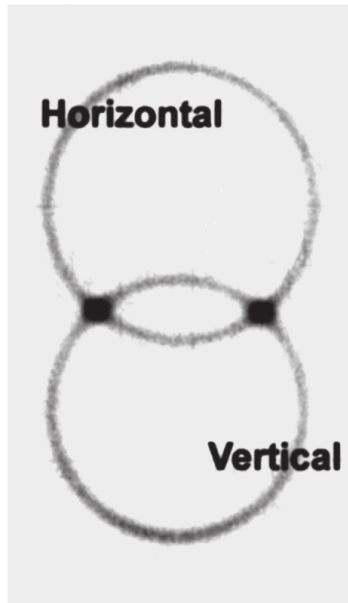


Fig. 2. Photons emerging from type II down-conversion (see text). Photograph taken perpendicular to the propagation direction. Photons are produced in pairs. A photon on the top circle is horizontally polarized while its exactly opposite partner in the bottom circle is vertically polarized. At the intersection points their polarizations are undefined; all that is known is that they have to be different, which results in entanglement. [中文](#)

To achieve projection of photons 1 and 2 into a Bell state we have to make them indistinguishable. To achieve this indistinguishability we superpose the two photons at a beam splitter (Fig. 1b). Then if they are incident one from each side, how can it happen that they emerge still one on each side? Clearly this can happen if they are either both reflected or both transmitted. In quantum physics we have to superimpose the amplitudes for these two possibilities. Unitarity implies that the amplitude for both photons being reflected obtains an additional minus sign. Therefore, it seems that the two processes cancel each other. This is, however, only true for a symmetric input state. For an antisymmetric state, the two possibilities obtain another relative minus sign, and therefore they constructively interfere^{15,16}. It is thus sufficient for projecting photons 1 and 2 onto the antisymmetric state $|\psi^-\rangle_{12}$ to place detectors in each of the outputs of the beam splitter and to register simultaneous detections (coincidence)¹⁷⁻¹⁹. [中文](#)

To make sure that photons 1 and 2 cannot be distinguished by their arrival times, they were generated using a pulsed pump beam and sent through narrow-bandwidth filters producing a coherence time much longer than the pump pulse length²⁰. In the experiment, the pump pulses had a duration of 200 fs at a repetition rate of 76 MHz. Observing the down-converted photons at a wavelength of 788 nm and a bandwidth of 4 nm results in a coherence time of 520 fs. It should be mentioned that, because photon 1 is also produced as part of an entangled pair, its partner can serve to indicate that it was emitted. [中文](#)

How can one experimentally prove that an unknown quantum state can be teleported? First, one has to show that teleportation works for a (complete) basis, a set of known states into which any other state can be decomposed. A basis for polarization states has just two components, and in principle we could choose as the basis horizontal

and vertical polarization as emitted by the source. Yet this would not demonstrate that teleportation works for any general superposition, because these two directions are preferred directions in our experiment. Therefore, in the first demonstration we choose as the basis for teleportation the two states linearly polarized at -45° and $+45^\circ$ which are already superpositions of the horizontal and vertical polarizations. Second, one has to show that teleportation works for superpositions of these base states. Therefore we also demonstrate teleportation for circular polarization. [中文](#)

Results

In the first experiment photon 1 is polarized at 45° . Teleportation should work as soon as photon 1 and 2 are detected in the $|\psi^-\rangle_{12}$ state, which occurs in 25% of all possible cases. The $|\psi^-\rangle_{12}$ state is identified by recording a coincidence between two detectors, f1 and f2, placed behind the beam splitter (Fig. 1b). [中文](#)

If we detect a f1f2 coincidence (between detectors f1 and f2), then photon 3 should also be polarized at 45° . The polarization of photon 3 is analysed by passing it through a polarizing beam splitter selecting $+45^\circ$ and -45° polarization. To demonstrate teleportation, only detector d2 at the $+45^\circ$ output of the polarizing beam splitter should click (that is, register a detection) once detectors f1 and f2 click. Detector d1 at the -45° output of the polarizing beam splitter should not detect a photon. Therefore, recording a three-fold coincidence d2f1f2 ($+45^\circ$ analysis) together with the absence of a three-fold coincidence d1f1f2 (-45° analysis) is a proof that the polarization of photon 1 has been teleported to photon 3. [中文](#)

To meet the condition of temporal overlap, we change in small steps the arrival time of photon 2 by changing the delay between the first and second down-conversion by translating the retroreflection mirror (Fig. 1b). In this way we scan into the region of temporal overlap at

the beam splitter so that teleportation should occur. [中文](#)

Outside the region of teleportation, photon 1 and 2 each will go either to f1 or to f2 independent of one another. The probability of having a coincidence between f1 and f2 is therefore 50%, which is twice as high as inside the region of teleportation. Photon 3 should not have a well-defined polarization because it is part of an entangled pair. Therefore, d1 and d2 have both a 50% chance of receiving photon 3. This simple argument yields a 25% probability both for the -45° analysis (d1f1f2 coincidences) and for the $+45^\circ$ analysis (d2f1f2 coincidences) outside the region of teleportation. Figure 3 summarizes the predictions as a function of the delay. Successful teleportation of the $+45^\circ$ polarization state is then characterized by a decrease to zero in the -45° analysis (Fig. 3a), and by a constant value for the $+45^\circ$ analysis (Fig. 3b). [中文](#)

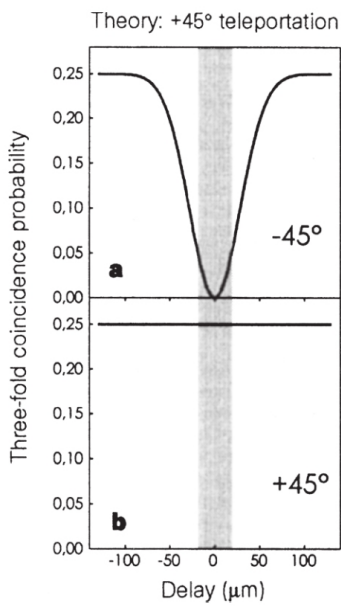


Fig. 3. Theoretical prediction for the three-fold coincidence probability between the two Bell-state detectors (f1, f2) and one of the detectors analysing the teleported state. The signature of teleportation of a photon polarization state at $+45^\circ$ is a dip to zero at zero delay in the three-fold coincidence rate with the detector analysing -45° (d1f1f2) (a) and a constant value for the detector analysis $+45^\circ$ (d2f1f2) (b). The shaded area indicates the region of teleportation.

The theoretical prediction of Fig. 3 may easily be understood by realizing that at zero delay there is a decrease to half in the coincidence rate for the two detectors of the Bell-state analyser, f1 and f2, compared with outside the region of teleportation. Therefore, if the polarization of photon 3 were completely uncorrelated to the others the three-fold coincidence should also show this dip to half. That the right state is teleported is indicated by the fact that the dip goes to zero in Fig. 3a and that it is filled to a flat curve in Fig. 3b. [中文](#)

We note that equally as likely as the production of photons 1, 2 and 3 is the emission of two pairs of down-converted photons by a single source. Although there is no photon coming from the first source (photon 1 is absent), there will still be a significant contribution to the three-fold coincidence rates. These coincidences have nothing to do with teleportation and can be identified by blocking the path of photon 1. [中文](#)

The probability for this process to yield spurious two- and three-fold coincidences can be estimated by taking into account the experimental parameters. The experimentally determined value for the percentage of spurious three-fold coincidences is $68\% \pm 1\%$. In the experimental graphs of Fig. 4 we have subtracted the experimentally determined spurious coincidences. [中文](#)

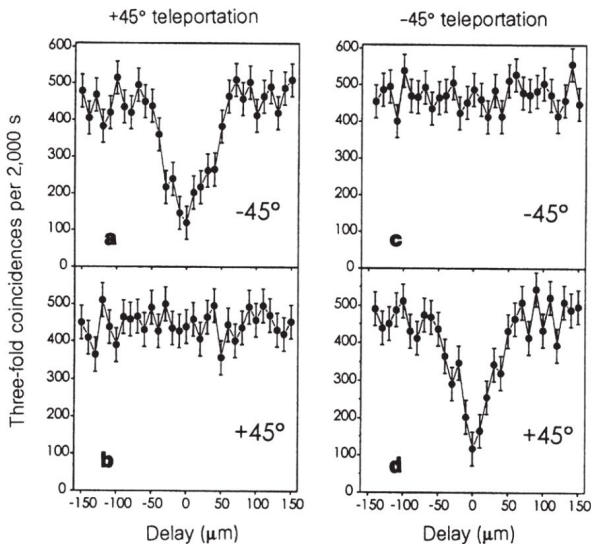


Fig. 4. Experimental results. Measured three-fold coincidence rates d1f1f2 (-45°) and d2f1f2 ($+45^\circ$) in the case that the photon state to be teleported is polarized at $+45^\circ$ (a and b) or at -45° (c and d). The coincidence rates are plotted as function of the delay between the arrival of photon 1 and 2 at Alice's beam splitter (see Fig. 1b). The three-fold coincidence rates are plotted after subtracting the spurious three-fold contribution (see text). These data, compared with Fig. 3, together with similar ones for other polarizations (Table 1) confirm teleportation for an arbitrary state. [中文](#)

The experimental results for teleportation of photons polarized under $+45^\circ$ are shown in the left-hand column of Fig. 4; Fig. 4a and b should be compared with the theoretical predictions shown in Fig. 3. The strong decrease in the -45° analysis, and the constant signal for the $+45^\circ$ analysis, indicate that photon 3 is polarized along the direction of photon 1, confirming teleportation. [中文](#)

The results for photon 1 polarized at -45° demonstrate that teleportation works for a complete basis for polarization states (right-hand column of Fig. 4). To rule out any classical explanation for the experimental results, we have produced further confirmation that our procedure works by additional experiments. In these experiments we teleported photons linearly polarized at 0° and at 90° , and also teleported circularly polarized photons. The experimental results are summarized in Table 1, where we list the visibility of the dip in three-

fold coincidences, which occurs for analysis orthogonal to the input polarization. [中文](#)

Table 1. Visibility of teleportation in three-fold coincidences

Polarization	Visibility
+ 45°	0.63 ± 0.02
−45°	0.64 ± 0.02
0°	0.66 ± 0.02
90°	0.61 ± 0.02
Circular	0.57 ± 0.02

[中文](#)

As mentioned above, the values for the visibilities are obtained after subtracting the offset caused by spurious three-fold coincidences. These can experimentally be excluded by conditioning the three-fold coincidences on the detection of photon 4, which effectively projects photon 1 into a single-particle state. We have performed this four-fold coincidence measurement for the case of teleportation of the + 45° and + 90° polarization states, that is, for two non-orthogonal states. The experimental results are shown in Fig. 5. Visibilities of $70\% \pm 3\%$ are obtained for the dips in the orthogonal polarization states. Here, these visibilities are directly the degree of polarization of the teleported photon in the right state. This proves that we have demonstrated teleportation of the quantum state of a single photon.

[中文](#)

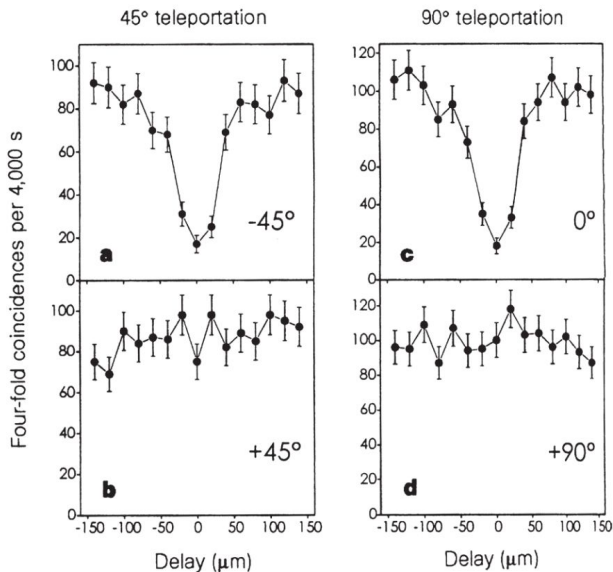


Fig. 5. Four-fold coincidence rates (without background subtraction). Conditioning the three-fold coincidences as shown in Fig. 4 on the registration of photon 4 (see Fig. 1b) eliminates the spurious three-fold background. **a** and **b** show the four-fold coincidence measurements for the case of teleportation of the $+45^\circ$ polarization state; **c** and **d** show the results for the $+90^\circ$ polarization state. The visibilities, and thus the polarizations of the teleported photons, obtained without any background subtraction are $70\% \pm 3\%$. These results for teleportation of two non-orthogonal states prove that we have demonstrated teleportation of the quantum state of a single photon. [中文](#)

The Next Steps

In our experiment, we used pairs of polarization entangled photons as produced by pulsed down-conversion and two-photon interferometric methods to transfer the polarization state of one photon onto another one. But teleportation is by no means restricted to this system. In addition to pairs of entangled photons or entangled atoms^{7,21}, one could imagine entangling photons with atoms, or phonons with ions, and so on. Then teleportation would allow us to transfer the state of, for example, fast-decohering, short-lived particles, onto some more stable systems. This opens the possibility of quantum memories, where the information of incoming photons is stored on trapped ions, carefully shielded from the environment. [中文](#)

Furthermore, by using entanglement purification²²—a scheme of improving the quality of entanglement if it was degraded by decoherence during storage or transmission of the particles over noisy channels—it becomes possible to teleport the quantum state of a particle to some place, even if the available quantum channels are of very poor quality and thus sending the particle itself would very probably destroy the fragile quantum state. The feasibility of preserving quantum states in a hostile environment will have great advantages in the realm of quantum computation. The teleportation scheme could also be used to provide links between quantum computers. [中文](#)

Quantum teleportation is not only an important ingredient in quantum information tasks; it also allows new types of experiments and investigations of the foundations of quantum mechanics. As any arbitrary state can be teleported, so can the fully undetermined state of a particle which is member of an entangled pair. Doing so, one transfers the entanglement between particles. This allows us not only to chain the transmission of quantum states over distances, where decoherence would have already destroyed the state completely, but it also enables us to perform a test of Bell's theorem on particles which do not share any common past, a new step in the investigation of the features of quantum mechanics. Last but not least, the discussion about the local realistic character of nature could be settled firmly if one used features of the experiment presented here to generate entanglement between more than two spatially separated particles^{23,24}. [中文](#)

(390, 575-579; 1997)

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Received 16 October; accepted 18 November 1997.

References:

1. Bennett, C. H. *et al.* Teleporting an unknown quantum state via dual classic and Einstein-Podolsky-Rosen channels. *Phys. Rev. Lett.* **70**, 1895-1899 (1993).
2. Schrödinger, E. Die gegenwärtige Situation in der Quantenmechanik. *Naturwissenschaften* **23**, 807-812; 823-828; 844-849 (1935).
3. Bennett, C. H. Quantum information and computation. *Phys. Today* **48(10)**, 24-30, October (1995).
4. Bennett, C. H., Brassard, G. & Ekert, A. K. Quantum Cryptography. *Sci. Am.* **267(4)**, 50-57, October (1992).
5. Mattle, K., Weinfurter, H., Kwiat, P. G. & Zeilinger, A. Dense coding in experimental quantum communication. *Phys. Rev. Lett.* **76**, 4656-4659 (1996).
6. Kwiat, P. G. *et al.* New high intensity source of polarization-entangled photon pairs. *Phys. Rev. Lett.* **75**, 4337-4341 (1995).
7. Hagley, E. *et al.* Generation of Einstein-Podolsky-Rosen pairs of atoms. *Phys. Rev. Lett.* **79**, 1-5 (1997).
8. Schumacher, B. Quantum coding. *Phys. Rev. A* **51**, 2738-2747 (1995).
9. Clauser, J. F. & Shimony, A. Bell's theorem: experimental tests and implications. *Rep. Prog. Phys.* **41**, 1881-1927 (1978).
10. Greenberger, D. M., Horne, M. A. & Zeilinger, A. Multiparticle interferometry and the superposition principle. *Phys. Today* August, 22-29 (1993).
11. Tittel, W. *et al.* Experimental demonstration of quantum-correlations over more than 10 kilometers. *Phys. Rev. Lett.* (submitted).
12. Zukowski, M., Zeilinger, A., Horne, M. A. & Ekert, A. "Event-ready-detectors" Bell experiment via entanglement swapping. *Phys. Rev. Lett.* **71**, 4287-4290 (1993).
13. Bose, S., Vedral, V. & Knight, P. L. A multiparticle generalization of entanglement swapping. (preprint).
14. Wootters, W. K. & Zurek, W. H. A single quantum cannot be cloned. *Nature* **299**, 802-803 (1982).
15. Loudon, R. *Coherence and Quantum Optics VI* (eds Everly, J. H. & Mandel, L.) 703-708 (Plenum, New York, 1990).
16. Zeilinger, A., Bernstein, H. J. & Horne, M. A. Information transfer with two-state two-particle quantum systems. *J. Mod. Optics* **41**, 2375-2384 (1994).
17. Weinfurter, H. Experimental Bell-state analysis. *Europhys. Lett.* **25**, 559-564 (1994).
18. Braunstein, S. L. & Mann, A. Measurement of the Bell operator and quantum teleportation. *Phys. Rev. A* **51**, R1727-R1730 (1995).
19. Michler, M., Mattle, K., Weinfurter, H. & Zeilinger, A. Interferometric Bell-state analysis. *Phys. Rev. A* **53**, R1209-R1212 (1996).
20. Zukowski, M., Zeilinger, A. & Weinfurter, H. Entangling photons radiated by independent pulsed sources. *Ann. NY Acad. Sci.* **755**, 91-102 (1995).
21. Fry, E. S., Walther, T. & Li, S. Proposal for a loophole-free test of the Bell inequalities. *Phys. Rev. A* **52**, 4381-4395 (1995).
22. Bennett, C. H. *et al.* Purification of noisy entanglement and faithful teleportation via

noisy channels. *Phys. Rev. Lett.* **76**, 722-725 (1996).

23. Greenberger, D. M., Horne, M. A., Shimony, A. & Zeilinger, A. Bell's theorem without inequalities. *Am. J. Phys.* **58**, 1131-1143 (1990).
24. Zeilinger, A., Horne, M. A., Weinfurter, H. & Zukowski, M. Three particle entanglements from two entangled pairs. *Phys. Rev. Lett.* **78**, 3031-3034 (1997).

Acknowledgements. We thank C. Bennett, I. Cirac, J. Rarity, W. Wootters and P. Zoller for discussions, and M. Zukowski for suggestions about various aspects of the experiments. This work was supported by the Austrian Science Foundation FWF, the Austrian Academy of Sciences, the TMR program of the European Union and the US NSF.

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量子隐形传态实验

鲍夫梅斯特等

基于量子物理的基本原理对信息以全新的方式进行操控，催生了量子信息技术，使我们有望实现超快速的量子计算和安全的量子密码。而由量子物理带来的其中一个神奇的现象是在远距离下量子态的瞬时转移：量子隐形传态。这项技术是利用纠缠态（在两个或多个粒子的纠缠态中，这些粒子的状态都是相互依赖的）的特性来实现的。在这篇文章中，来自因斯布鲁克大学的安东·蔡林格和他的同事们报道了第一个量子隐形传态的实验演示。这个实验是将一个光子的偏振态转移给远处另一个处在纠缠态的光子。自这个实验以后，如今已经可以在一百千米以上的距离实现量子隐形传态。

[英文](#)

我们实验演示了量子隐形传态，也就是将量子系统的状态传递到任意距离之外并加以重建。本次实验过程涉及三个光子，第一个光子携带将被转移的偏振信息。第二个和第三个光子处于纠缠态，对第一个和第二个光子进行联合测量，第三个光子就可以获得第一个光子的偏振信息。第三个光子与第一个光子之间的距离可以任意远。量子隐形传态将成为量子计算网络的关键组成。

[英文](#)

隐形传态是想通过在远处重现的方法来实现旅行的梦想。远距传送的对象可以完全由其性质来表示，在经典物理中这些性质可以由测量决定。要在一定距离之外造出对象的一个副本，我们并不需要原来的部分和零件，只要把扫描得到的信息传送过去用来重建对象就可以了。但是这样得到的原件的副本有多精确？如果那些部分和零件是电子，原子和分子呢？它们的个体量子性质会是什么情况？根据海森堡的测不准原

理，这些个体量子性质是无法以任意精度测量的。 [英文](#)

本内特等^[1]提出，一个粒子的量子态可以被转移到另一个粒子上，前提是在转移过程中关于这个态的信息不可知，这就是量子隐形传态过程。其前提条件可以由作为量子力学本质特征的纠缠^[2]来实现。它描述了比任何经典的相关都要强的量子系统之间的关联。 [英文](#)

量子信息传送的可能性是新兴的量子通信和量子计算领域的基石之一^[3]。虽然量子信息处理的理论描述发展很快，但是由于操纵量子系统的困难性，新方案的实验演示相对滞后。除了已经演示了充满希望的量子密码^[4]（第一个被证实的保密通信方式）之外，我们还只是在前不久又成功演示了量子密集编码这种基于量子力学实现增强数据压缩的可能性^[5]。实验进展如此之慢的主要原因在于，虽然存在产生纠缠光子对的方法^[6]，但原子的纠缠到最近才被证实^[7]，并且目前为止无法产生两个量子以上的纠缠态。 [英文](#)

本文中我们报道了量子隐形传态的首次实验证明。通过参量下转换产生纠缠光子对，并利用双光子干涉测量来分析纠缠，我们可以做到将量子特性（在我们的实验中是偏振态）从一个光子转移到另一个光子。本实验发展的方法将在量子通信领域以及未来量子力学基础检验中发挥重要作用。 [英文](#)

问题阐述

为了阐明量子信息转移的问题，我们假设艾丽斯有一个粒子处于某个量子态 $|\psi\rangle$ 并且她希望远处的鲍勃也有一个粒子处于这个态。当然，一种可能的方式是直接把自己的粒子送到鲍勃那里。但是如果艾丽斯和鲍勃之间的通信通道不够好不足以保持必要的量子相干性，或者传送过程需要的时间太长（若 $|\psi\rangle$ 是更复杂的或者更大的对象的态函数，就会很容易出现这些情况），艾丽斯和鲍勃能采取什么策略呢？ [英文](#)

正如前面提到的一样，因为量子系统的态是不能完全由测量确定的，艾丽斯对 $|\psi\rangle$ 所能进行的测量，都不能精确到让鲍勃能够重建这个态。量子叠加性原理可以使量子系统同时处于几个态的叠加。对量子系统进行测量会迫使它处于其中的一个态，这经常被称为投影假设。我们

可以通过一个光子的例子来说明这个重要的量子特征。这个光子可以处于水平偏振或者垂直偏振，分别以 $|\leftrightarrow\rangle$ 和 $|\updownarrow\rangle$ 表示。其偏振态甚至可以是这两个态的普遍叠加

$$|\psi\rangle = \alpha |\leftrightarrow\rangle + \beta |\updownarrow\rangle \quad (1)$$

其中 α 和 β 是两个复数满足 $|\alpha|^2 + |\beta|^2 = 1$ 。为了让这个例子更具普遍性，我们可以把公式(1)中的态 $|\leftrightarrow\rangle$ 和 $|\updownarrow\rangle$ 换作 $|0\rangle$ 和 $|1\rangle$ ，来表示任何双态量子系统的两个态。 $|0\rangle$ 和 $|1\rangle$ 的叠加被称为量子比特，以显示量子物理为信息科学引入新的可能性^[8]。 [英文](#)

如果一个处于 $|\psi\rangle$ 态的光子通过一个偏振分束器（这种器件反射水平偏振光而透射垂直偏振光），则在反射光束中找到该光子的概率是 $|\alpha|^2$ ，在透射光束中找到该光子的概率是 $|\beta|^2$ 。测量的行为使得普通态函数 $|\psi\rangle$ 被投影到 $|\leftrightarrow\rangle$ 或者 $|\updownarrow\rangle$ 上。我们的结论是：量子力学的规则，特别是投影假设，使得艾丽斯不可能对 $|\psi\rangle$ 进行一次测量以得到所有必要的信息来重建这个态。 [英文](#)

量子隐形传态的概念

尽管量子力学的投影假设看上去阻止了艾丽斯将 $|\psi\rangle$ 态提供给鲍勃的意图，本内特等^[1]却意识到就是这个投影假设使得 $|\psi\rangle$ 从艾丽斯到鲍勃的隐形传态成为可能。在隐形传态过程中，艾丽斯将对自己这边的量子态进行测量破坏，这时，鲍勃那边才接收到这个量子态，这个过程中，两个人都没有获知 $|\psi\rangle$ 态的信息。最初由艾丽斯和鲍勃共享的处于纠缠态的辅助粒子对在这个隐形传态方案中起到关键作用。 [英文](#)

假定艾丽斯想要传送的粒子1处于初始态 $|\psi\rangle_1 = \alpha |\leftrightarrow\rangle_1 + \beta |\updownarrow\rangle_1$ （图1a），并且艾丽斯和鲍勃共享的纠缠粒子对，即粒子2和粒子3处于下列态中：

$$|\psi\rangle_{23} = \frac{1}{\sqrt{2}} (|\leftrightarrow\rangle_2 |\updownarrow\rangle_3 - |\updownarrow\rangle_2 |\leftrightarrow\rangle_3) \quad (2)$$

这个纠缠粒子对是 $|\leftrightarrow\rangle_2 |\updownarrow\rangle_3$ 态和 $|\updownarrow\rangle_2 |\leftrightarrow\rangle_3$ 态等量叠加的一个简单量子系统。纠缠态不包含任何个体粒子的信息，它仅仅表明两个粒子是处于正

交的态。纠缠对的一个重要特性就是当对其中一个粒子进行测量而将其投影到比如说 $|\leftrightarrow\rangle$ 上，另一个粒子的态就确定为 $|\downarrow\rangle$ ，反过来也是一样。对一个粒子的测量如何能够瞬间影响另一个可以是任意远的粒子的态？爱因斯坦还有其他很多杰出物理学家干脆不能接受这种“幽灵般的超距作用”。但是纠缠态的这个性质已经被很多实验所证实（请看参考文献9和10）。 英文

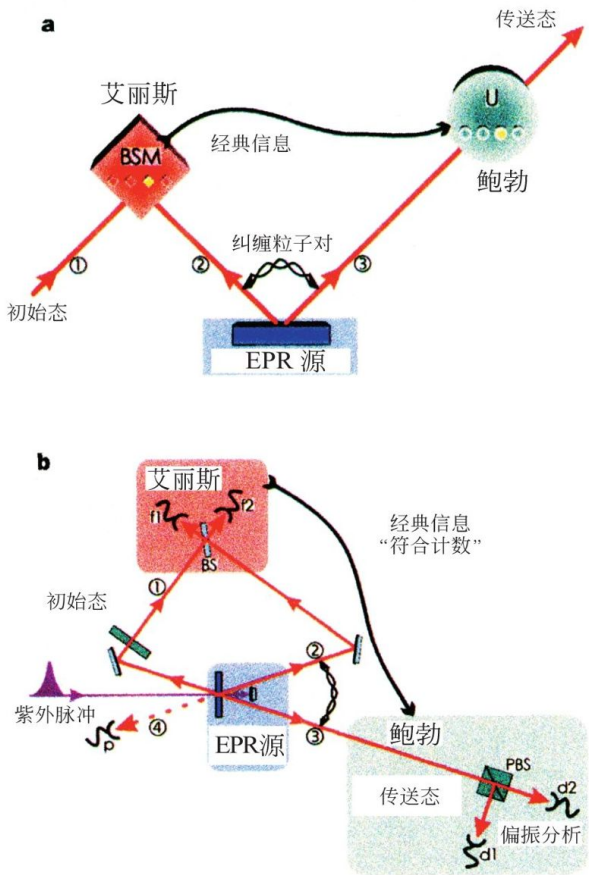


图1．表现量子隐形传态相关原理（a）和实验装置（b）的示意图。a，艾丽斯想把自己的量子系统也就是粒子1所处的初始态传送给鲍勃。艾丽斯和鲍勃共享一个从EPR源发出的辅助纠缠粒子对2和3。艾丽斯接着对初始粒子1和辅助对中的一个粒子进行一个联合贝尔态测量，将其投影到一个纠缠态上。在她将测量结果以经典信息形式传送给鲍勃后，他就可以对另一个辅助粒子进行么正变换，使之处于初始粒子1的状态中。b，一束紫外线脉冲通过非线性晶体时产生了辅助光子对2和3。逆反射后第二次穿过晶体时这个紫外脉冲又产生一对光子，其中一个将被制备到待传递的光子1的初始态，另一个用作触发器，表示一个待传态的光子已经上路。于是，艾丽斯查看经过分束器BS后初始光子和一个辅助光子叠加时的符合计数。鲍勃在收到艾丽斯已经在探测器f1和f2处获得验证贝尔态 $|\psi\rangle_{12}$ 的符合计数的经典信息后，就知道他的光子3已处于光子1的初始态中，并可用偏振分光器PBS和探测器d1和d2进行偏振分析来验证。探测器p提供光子

隐形传态方案如下面所述。艾丽斯现有粒子2和处于初始态 $|\psi\rangle_1$ 的粒子1，粒子2与鲍勃处的粒子3处于纠缠态。关键之处是对粒子1和粒子2进行一个特定的测量，将它们投影到纠缠态上：

$$|\psi^-\rangle_{12} = \frac{1}{\sqrt{2}} (|\leftrightarrow\rangle_1 |\downarrow\rangle_2 - |\downarrow\rangle_1 |\leftrightarrow\rangle_2) \quad (3)$$

这仅仅是任意双粒子态可以分解成的四个可能的最大纠缠态之一。双粒子任意态在四个最大纠缠态组成的一组正交完备基中任何一个态上的投影测量叫贝尔态测量。公式3中的态和其他三个最大纠缠态的不同之处在于交换粒子1和粒子2将导致其符号改变。 $|\psi^-\rangle_{12}$ 态的这个独特的反对称特征在实验确认也就是在这个态的测量中将起到重要作用。 [英文](#)

量子物理预言^[1]当粒子1和2被投影到 $|\psi^-\rangle_{12}$ 态时，粒子3将被即时投影到粒子1的初始态。原因如下：因为我们测量得知粒子1和2处于 $|\psi^-\rangle_{12}$ 态中，所以我们知道无论粒子1处于任何态，粒子2一定处于正交态，也就是和粒子1的态正交的态中。但是我们一开始将粒子2和3置于 $|\psi^-\rangle_{23}$ 态中，也就是说粒子2也和粒子3正交。要实现这一点唯一的可能就是粒子3处于和粒子1的初始态相同的态中。由此粒子3的终态就是

$$|\psi\rangle_3 = \alpha|\leftrightarrow\rangle_3 + \beta|\downarrow\rangle_3 \quad (4)$$

注意在贝尔态测量过程中粒子1因为与粒子2纠缠而失去了自身特征。因此艾丽斯这边的 $|\psi\rangle_1$ 态在隐形传态过程中被破坏。 [英文](#)

这个结果（公式4）值得进一步讨论。从粒子1到粒子3的量子信息的转移可以是通过任意距离，所以才有隐形传态的名字。实验证明量子纠缠能够建立在10千米量级的距离上^[11]。注意隐形传态方案中艾丽斯不需要知道鲍勃在哪里。另外不光是艾丽斯，其他任何人都不用知道粒子1的初始态。在进行贝尔态测量时，它甚至可以是在量子力学意义上完全未定义的。正像本内特等^[1]已经指出过的，当粒子1自己是一个纠缠对中的一员因而没有自己的明确定义的性质时，就是这种情况。这最终导致纠缠交换^[12,13]。 [英文](#)

另外重要的一点是贝尔态测量不揭示任何一个粒子性质的任何信息。这是为什么利用相干双粒子叠加的量子隐形传态能够成功，而任何单粒子叠加的测量都会失败的原因。未能获取任一粒子的任何信息的事实，也是量子隐形传态并不违反量子不可克隆定理^[14]的原因。在成功的隐形传态之后，粒子1不再处于初始态，因而粒子3确实是隐形传态的结果而不是一个克隆。 [英文](#)

一个完整的贝尔态测量不仅能给出两个粒子1和2处于反对称态的结果，我们还可能发现它们处于其他三个纠缠态中的任何一个的概率都是相等的25%。如果发生这种情况，粒子3就处于三个不同的态中的一个。接着鲍勃可以在通过经典通信通道收到艾丽斯获取的是哪一个贝尔态的信息后，通过选择相应的变换，在与粒子1所处态无关的情况下，将粒子3置于粒子1的初始态中。我们要着重强调，即使像前面所讨论的那样我们选择只确认四个贝尔态中的一个，隐形传态仍然可以成功实现，尽管只是在四分之一的事例中。 [英文](#)

实验的实现

实现隐形传态需要生成和测量纠缠态。任何实验实现都要面临这两个难题。到目前为止，能够作出纠缠态的实验技术寥寥无几，而且没有成功的实验程序来确认任何一种量子系统的所有四个贝尔态。虽然如此，纠缠光子对可以由简易方法产生并被投影到至少两个贝尔态上。

[英文](#)

我们通过参量下转换产生纠缠光子对2和3。在这项技术中，非线性晶体中进来一个泵浦光子可以即时衰变为两个光子。在二型参量下转换情形中，这两个光子处于公式2给出的态（图2）^[6]。 [英文](#)

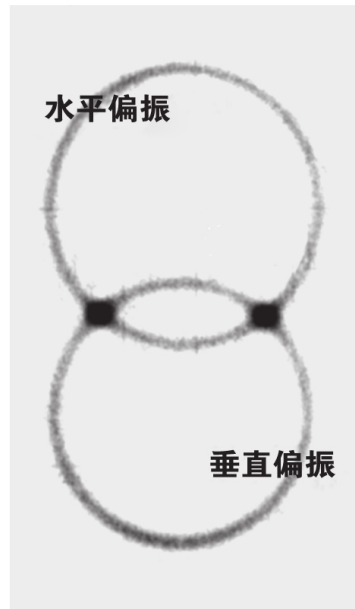


图2．二型参量下转换产生的光子（见正文）。相片与传播方向垂直。光子成对产生。顶圈的光子水平偏振，其严格相反的底圈同伴为垂直偏振。在相交的两点它们的偏振态是不明确的，我们只知道它们必须是不同的，这就导致纠缠。[英文](#)

要将光子1和2投影到一个贝尔态上我们必须让它们变得不可区分。为实现这个不可区分性我们将这两个光子在分束器处叠加（图1b）。这样的话，如果它们从两边一边一个地入射，能不能做到出射时也是一边一个呢？显然这是可能的，只要它们都被反射或者都被透射就行。在量子物理中我们必须将这两个可能的振幅叠加。么正性意味着两个光子都被反射的那个可能情形的振幅需要多加一个负号。这样的话这两个过程看上去互相抵消。但是只有对称入射态才是这种情况。对于反对称入射态，这两个可能情形要再加一个相对的负号，这样它们之间的干涉是相长的^[15,16]。由此，只要将探测器放在分束器的每个输出端记录同时发生的响应（符合计数），就可以将光子1和2投影到反对称态 $|\psi^-\rangle_{12}$ ^[17-19]。[英文](#)

为了确保不能通过到达时间来区分光子1和2，我们通过脉冲泵浦光束产生光子1和2并使其通过窄带宽滤波器来产生一个比泵浦脉冲长度长得多的相干时间^[20]。在实验中泵浦脉冲持续时间为200 fs，重复率为76 MHz。观测下转换产生的光子（该光子波长为788 nm，带宽为4 nm）得到相干时间为520 fs。这里应当提到的是，由于光子1也是作为纠缠对

的一部分产生的，可以用其同伴来显示它已被发出。 [英文](#)

如何用一个实验证明未知量子态被隐形传送？首先要证明隐形传态能够在—组（完备）基矢上成功实现，任何其他态都能分解到这组已知基矢上。偏振态的基矢只有两个成分，原理上我们可以把源发射的水平和垂直偏振作为基矢。但是因为这两个方向在我们实验中是优先方向，这种演示不能证明隐形传送对任何普遍叠加态都能实现。出于这个原因，在第一个实验中我们选择 -45° 和 $+45^\circ$ 两个线性偏振态作为拟传送态的基矢。它们都已经是水平和垂直偏振的叠加。其次，我们必须证明对这些基矢的叠加也能实现隐形传态。为此我们还证明了圆偏振的隐形传态。 [英文](#)

实验结果

在第一个实验中光子1处于 45° 偏振。在所有可能情形中，光子1和2被检测到处于 $|\psi^-\rangle_{12}$ 态的概率是25%。一旦出现这种情形，隐形传态就应当实现。 $|\psi^-\rangle_{12}$ 态的确认是通过置于分束器后面两个探测器f1和f2的符合计数来实现的（图1b）。 [英文](#)

如果我们探测到一个f1f2（探测器f1和f2之间的）符合事例，那么光子3应当也是 45° 偏振。光子3的偏振态的分析方法是让它通过一个选择 $+45^\circ$ 和 -45° 偏振的偏振分束器。若要证明隐形传态的实现，当探测器f1和f2响应时，必须只有偏振分束器 $+45^\circ$ 输出端的探测器d2有响应，也就是记录下了一次探测，而偏振分束器 -45° 输出端的探测器d1不应探测到光子。因此，一个三重符合计数d2f1f2（ $+45^\circ$ 偏振分析）的记录，加上三重符合计数d1f1f2（ -45° 偏振分析）的缺失，就成为光子1的偏振态已经被隐形传态到光子3的证据。 [英文](#)

为满足时间重叠条件，我们通过平移逆反射镜改变第一次和第二次下转换之间的延迟来微调光子2的到达时间（图1b）。用这种办法，我们逐渐进入分束器处时间重叠的区间，保证隐形传态发生。 [英文](#)

在隐形传态区间之外，光子1和2各自可能独立奔向f1或者f2。因此在f1和f2得到一个符合计数的概率是50%。这个概率是在隐形传态区间中的两倍。光子3因为是纠缠对中的一员，所以不应有明确定义的偏振。

这样的话，d1和d2都有50%的可能接收到光子3。这个简单的论证得到的结果是，在隐形传态区间之外， -45° 偏振分析（d1f1f2符合计数）和 $+45^\circ$ 偏振分析（d2f1f2符合计数）都有25%的概率。图3总结了作为时间延迟函数的预测概率值。 -45° 分析下降到零（图3a）和 $+45^\circ$ 分析保持为一个常数（图3b），表征 $+45^\circ$ 偏振态的隐形传态得到成功实现。

英文

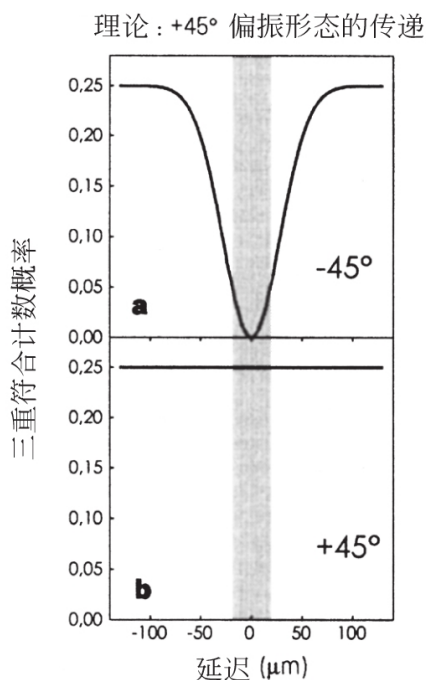


图3．两个贝尔态探测器（f1,f2）和分析被传递态的两个探测器之一的三重符合计数概率的理论预期。 $+45^\circ$ 光子偏振态传递的特征是：在零延迟处， -45° 偏振分析探测器三重符合计数率（d1f1f2）有一个到零概率值的下降（a），而 $+45^\circ$ 分析探测器三重符合计数率（d2f1f2）保持为常数（b）。阴影区为隐形传态区间。

英文

图3中的理论预计图可以这样来简单理解：与隐形传态区间之外相比较，在延迟为零时，两个贝尔态探测器f1和f2的符合计数率下降一半；如此一来，如果光子3的偏振与其他光子完全无关，三重符合计数也应该降到一半。在图3a中曲线下降一直到零而在图3b中被填平成为平坦曲线，表明设计的隐形传态得到实现。

英文

需要指出的是，与光子1、2和3的产生同样可能发生的是单一源发出两对下转换光子。虽然这种情况中没有光子来自第一个源（光子1未

出现)，但是它对三重符合计数率仍有显著贡献。这些符合计数与隐形传态无关，可以用阻断光子1路径的办法确认。[英文](#)

这一产生乱真二重和三重符合计数的过程发生的概率可以从实验参数估计。由实验确定的乱真三重符合计数的百分比是 $68\% \pm 1\%$ 。图4中的实验图形中我们已经扣除这个实验确定的乱真符合计数。[英文](#)

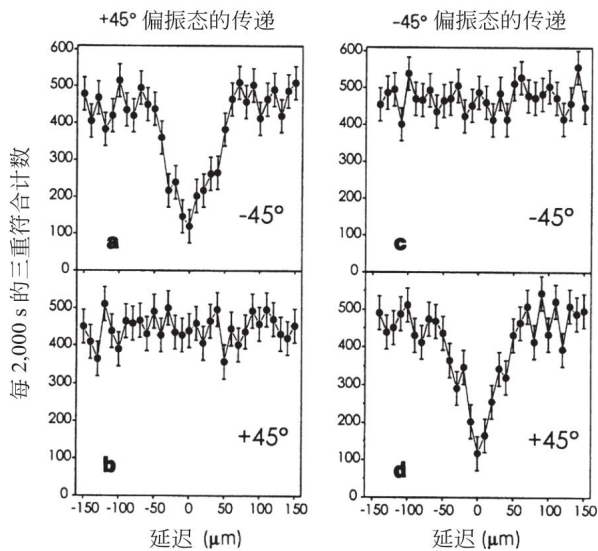


图4．实验结果。在待传光子为 + 45°偏振 (a和b) 或者 -45°偏振 (c和d) 的情况下，测量 d1f1f2 (-45°) 和 d2f1f2 (+ 45°) 三重符合计数率。画出的符合计数率是光子1和2分别到达艾丽斯的分束器的延迟的函数（见图1b），并扣除了乱真三重计数的贡献（见正文）。这些数据与图3对比，再加上其他偏振的类似结果（表1），证实了任意一个态都可被传递。[英文](#)

图4左栏是 + 45°偏振光子的隐形传态的实验结果；我们应当把图4a和b与图3中的理论预计曲线相比较来看。-45°分析中的猛烈下降和 + 45°分析中的稳定信号表明光子3与光子1的偏振方向相同，证实了隐形传态的实现。[英文](#)

-45°偏振的光子1的结果证明能够对一组完备的偏振基态实现隐形传态（图4右栏）。为了排除对实验结果的任何经典解释，我们用另外的实验进一步证实我们的方法是成功的。在这些附加实验中我们隐形传送了0°和90°的线偏振光子以及圆偏振光子，结果总结在附表1中。实验中与入射偏振正交方向的三重符合计数出现下降，表中列出了这个下降的可见度。[英文](#)

表1. 三重符合计数下隐形传态的可见度

偏振方向	可见度
+45°	0.63 ± 0.02
-45°	0.64 ± 0.02
0°	0.66 ± 0.02
90°	0.61 ± 0.02
圆偏振	0.57 ± 0.02

英文

如前所述，这些可见度是扣除乱真三重符合计数引起的偏差之后得到的数值。实验上排除这些计数的办法是对三重计数再附加一个光子4计数的条件。这使得光子1实际上被投影到一个单粒子态上。我们将这个四重符合计数测量方法用到 + 45°和 + 90°偏振态这两个非正交态的隐形传态中。实验结果在图5中给出。得到的正交偏振态下降的可见度在 70% ± 3%。这些可见度直接就是被传态光子在其本态的偏振度。这表示我们已经证明了单个光子的量子态的隐形传递。

英文

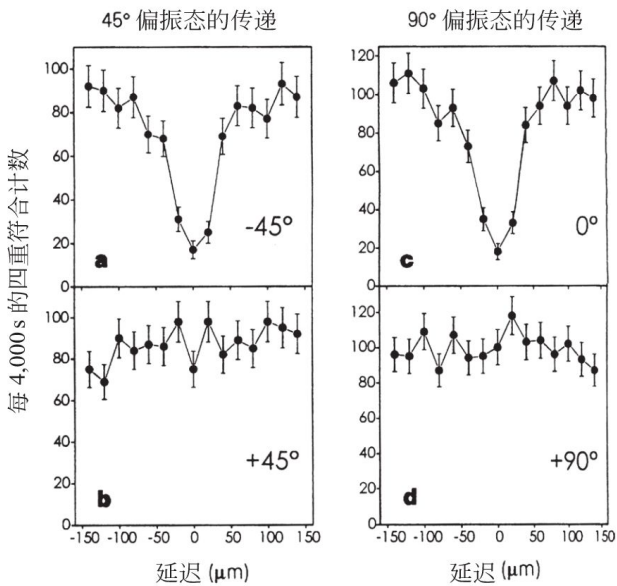


图5 . 四重符合计数率 (未扣除背景)。对图4的三重符合计数附加一个光子4计数的条件 (见图1b) 消除了乱真三重计数的背景。a和b显示传递 + 45°偏振态的四重符合计数测量；c和d是 + 90°偏振态的结果。在没有去除背景的情况下，得到的可见度，也就是被传态光子的偏振度，是70% ± 3%。这两个非正交态的传递结果表明了我们已经证实单个光子的量子态的隐形传态。

英文

我们的实验使用脉冲下转换产生的偏振纠缠光子对，并利用双光子干涉测量法来将一个光子的偏振态传递给另一个光子。但是隐形传态不只局限于这个系统。除了纠缠光子对或者纠缠原子对^[7,21]，还可以设想光子和原子之间纠缠，声子和离子之间纠缠等等。隐形传态使得我们能够把比如快速退相干的短寿命粒子的态转移到其他更稳定的系统中，这使得量子存储成为可能。在量子存储中，进来的光子的信息被储存在被俘获的离子上，外界的影响被很好地屏蔽掉。 [英文](#)

纠缠纯化^[22]是一种在存储粒子或在噪声信道传送粒子的过程中因退相干导致纠缠退化时改进纠缠质量的方案。利用纠缠纯化可以更进一步将一个粒子的量子态传至异地，哪怕当前量子通道的质量很差并且使得传递粒子本身很可能把脆弱的量子态破坏。在不利环境中保存量子状态的可行性在量子计算领域中会带来很大优势。隐形传态的方案还可以用于两台量子计算机之间的通信。 [英文](#)

量子隐形传态不仅仅是量子信息处理任务的一个重要组成，它还为量子力学基础提供新的实验和研究方法。既然任意一个态都可以被传递，作为一个纠缠对中一员的粒子的完全未确定的量子态也可以被传递。这种做法等于在粒子间传递纠缠。这样我们不但能够用长距离链式传递量子态解决退相干在途中破坏量子态的问题，而且能够对没有共同历史的粒子进行贝尔定律检测（量子力学特征研究的新步骤）。最后同样重要的一点是，如果利用本文描述的实验要素来产生两个以上的空间分离粒子的纠缠，就可能确实解决自然界定域实在特征的争论^[23,24]。 [英文](#)

（何钧 沈乃澍 翻译；陆朝阳 李军刚 审稿）

Localization of Light in a Disordered Medium

D. Wiersma *et al.*

Quantum physics implies that particle diffusion inside disordered materials may be inhibited by destructive wave interference, if the disorder is sufficiently pronounced. This phenomenon of strong localization—or “Anderson localization”, as it was originally described by physicist Philip Anderson—affects not only the behaviour of electrons in many solids, but that of photons as well. Here Diederik Wiersma and colleagues provided experimental confirmation of Anderson localization for light in semiconductor powders. They studied light transmission through gallium arsenide in a crystal and in powders with various particle sizes. They found a sharp threshold of particle size at which disorder-induced localization ultimately blocks light transmission, causing the transmission coefficient through a sample to decrease exponentially with sample thickness rather than linearly. [中文](#)

Among the unusual transport properties predicted for disordered materials is the Anderson localization¹ phenomenon. This is a disorder-induced phase transition in the electron-transport behaviour from the classical diffusion regime, in which the well-known Ohm’s law holds, to a localized state in which the material behaves as an insulator. The effect finds its origin in the

interference of electrons that have undergone multiple scattering by defects in the solid²⁻¹⁰. A similar phenomenon is anticipated for multiple scattering of electromagnetic waves, but with one important simplification: unlike electrons, photons do not interact with one another. This makes transport of photons in disordered materials an ideal model system in which to study Anderson localization¹⁰⁻¹⁷. Here we report direct experimental evidence for Anderson localization of light in optical experiments performed on very strongly scattering semiconductor powders. [中文](#)

MULTIPLE scattering of light is a common phenomenon in daily life, occurring for example in sugar, fog, white paint and clouds. The propagation of light in these media can in general be described by a normal diffusion process. For diffusion of light through a disordered material the same Ohm's law holds as for diffusion of electrons through any common resistor: the transmission, or conductance, decreases linearly with the system length (thickness). [中文](#)

Anderson localization brings classical diffusion to a complete halt. That is, on increasing the amount of scattering beyond a critical value, the material makes a transition into a localized state (see Fig. 1). This transition can best be observed in the transmission properties of the system. In the localized state, the transmission coefficient decreases exponentially instead of linearly with the thickness of a sample. At the transition, the transmission coefficient is expected to have a power-law dependence on the inverse thickness, which is probably quadratic^{12,18}. [中文](#)

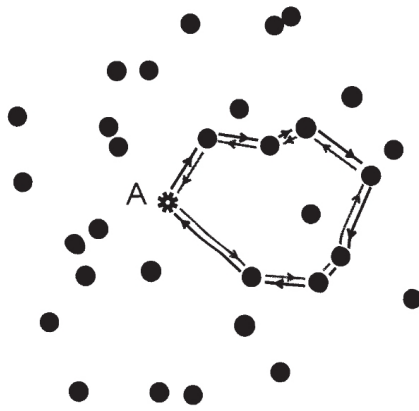


Fig. 1. Anderson localization of waves in disordered systems originates from interference in multiple elastic scattering. Here we consider a light source (like an excited atom emitting a photon) in a disordered medium at position A. The light source is denoted by a star symbol and the spheres denote the scattering elements. A random light path that returns to the light source can be followed in two opposite directions. The two waves which propagate in opposite directions along this loop will acquire the same phase and therefore interfere constructively in A. This leads to a higher probability of the wave coming back to A and consequently a lower probability of propagating away from A. On decreasing the mean free path l , the probability for such looped paths increases and at strong enough scattering the system makes a phase transition from the normal conducting state into a localized state, due to interference. In the localized regime, the system behaves as a non-absorbing insulator. Light which is incident on, for example, a slab would be almost completely reflected and the remaining transmission would decrease exponentially with the slab thickness. [中文](#)

The main difficulty in the search for localization of light has been the realization of strong enough scattering. The appropriate measure for the amount of scattering is the mean free path l for the light in the medium, times the magnitude of the wavevector k . Localization is expected for $kl \leq 1$ (ref. 19), which is known as the (modified) Ioffe–Regel criterion. This criterion can be understood intuitively if one realizes that below $kl=1$, the electric field can not even perform one oscillation before the wave is scattered again. So far, localization effects have been reported only for microwaves in a two-dimensional system of rods²⁰ and for microwaves in a confined geometry (a copper tube filled with metallic and dielectric spheres)^{21,22}. In the latter experiment the absorption was very large, which makes the interpretation of the data complicated. The disadvantage of

experiments with microwaves compared to light waves is that it is difficult to avoid absorption. [中文](#)

We have been able to realize very strongly scattering samples for light waves, using semiconductor powders. Semiconductors can have a very large refractive index, while, for wavelengths in the bandgap, the absorption is extremely small. We used light at wavelength $\lambda = 1,064$ nm, at which the absorption coefficient κ of pure GaAs is $\kappa \ll 1 \text{ cm}^{-1}$ and the refractive index is 3.48. Our samples consist of pure (99.999%) gallium arsenide (GaAs) crystals which were ground (as a suspension in methanol) by hand in a ceramic mortar and in a planetary micromill at low speed. By varying the grinding time, we obtained samples with different average particle sizes and thereby different amounts of scattering. In grinding semiconductors one has to be careful not to introduce absorption at the wavelength at which the experiments are performed. For a powder, surface states could become more important and the grinding process (even if performed with little force) could introduce strain or lattice deformations. Surface states, strain and lattice deformations can lead to absorption tails at the edge of the bandgap. We have characterized the change of the band edge of our material by measuring the temperature dependence of the transmission (Fig. 2). [中文](#)

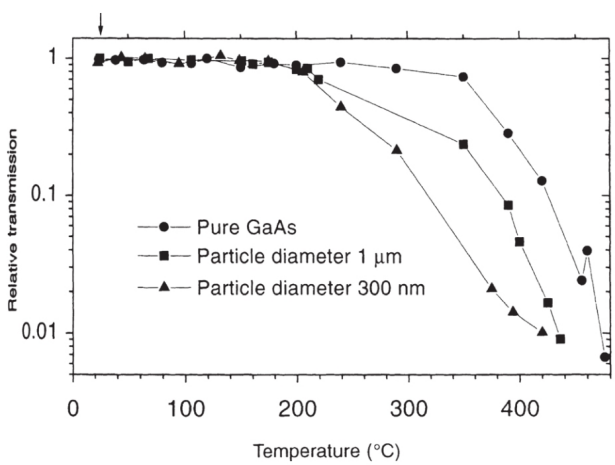


Fig. 2. Comparison of the temperature dependence of the transmission of pure GaAs crystals

and powders. Data obtained using particles of size of 1 μm and 300 nm are shown. The transmission of the powder samples is measured at a thickness where the total transmission equals 1% at room temperature. All curves are scaled to have a maximum of 1. On increasing the temperature T , the bandgap shifts to lower energies $E_g(T)$ corresponding to higher wavelengths $\lambda_g = 1.24/E_g$ (in μm). The temperature dependence is given by the empirical relation: $E_g(T) = E_g(0) - \alpha T^2 / (T + \beta)$, where (for GaAs) $E_g(0) = 1.522$, $\alpha = 8.871 \times 10^{-4}$ and $\beta = 572$, with T in K. This temperature-dependent shift enables the scanning of the region of the bandgap around the laser wavelength, without changing the laser wavelength itself. For example, a temperature of 200 $^\circ\text{C}$ corresponds to a wavelength shift of 65 nm. The arrow at top left shows the temperature where we performed all other experiments. We note that the band edge becomes less steep upon grinding the GaAs crystal; this is probably due to the increased importance of surface states and, for example, lattice deformations. But the region close to the laser wavelength remains unabsorbing. [中文](#)

We observe (Fig. 2) that the band edge indeed becomes less steep on grinding, and that the onset of absorption shifts into the bandgap. It is also clear, however, that the region of the absorption tails is still far enough (65 nm) below our laser wavelength as to ensure that these tails will not introduce absorption in our experiments. [中文](#)

To characterize the mean free path l of our samples, we used coherent backscattering. This phenomenon is a general interference effect between counter-propagating waves, which leads to a narrow cone in exact backscattering²³. It is seen as the precursor to Anderson localization and is therefore also called “weak localization of light”^{24,25}. The width of the backscattering cone and the angle of its cusp are inversely proportional to l (refs 26, 27) and therefore enable the determination of the amount of scattering inside the samples. Furthermore, the cusp is due to a summation up to (in principle) infinite path length, and is therefore only present in the absence of absorption²⁶⁻²⁸. In Figure 3, we show backscattering cones for a coarse-grained (Fig. 3a) and a fine-grained (Fig. 3b) powder with an average particle diameter of 10 μm and 1 μm , respectively. From the angle of the cusp we find for the coarse-grained powder $l = 8.5 \mu\text{m}$ and hence $kl = 76$. For the fine-grained powder we find $l \approx 0.17 \mu\text{m}$ which corresponds to $kl \approx 1.5$. The observed value of $kl = 1.5$ is four times smaller than the smallest kl values that have been reported so far³⁰ for

light waves. The shape of the coherent backscattering cone at the localization transition is interesting from both an experimental and a theoretical point of view, but will be discussed elsewhere. [中文](#)

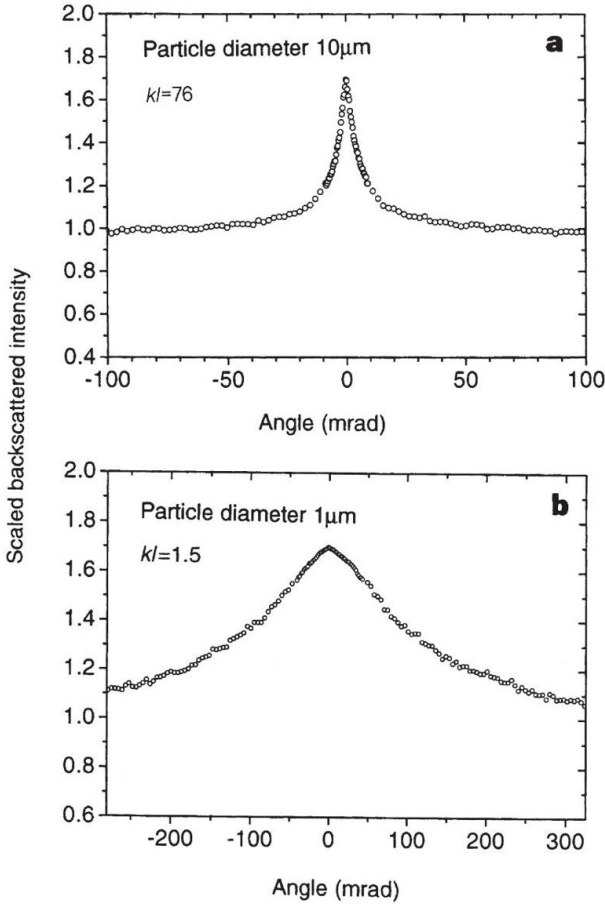


Fig. 3. Coherent backscattering cones from coarse-grained (a) and fine-grained (b) GaAs powder. The samples are strongly polydisperse with an average particle diameter of 10 μm and 1 μm , respectively. The sample is illuminated with a mode-locked Nd:YAG laser operating at 76 MHz, with a wavelength of 1,064 nm, pulse duration 100 ps, beam diameter 6 mm and incident power 100 mW. In all experiments we have checked that nonlinear absorption processes like two-photon absorption do not play a role; this was done by lowering the incident power to 20 mW, and finding that this reduction did not influence the results. Detection is performed in the polarization-conserving channel. The mean free path is calculated from the angle of the cusp²⁷, taking into account internal reflection²⁹. This yields $l=8.5 \mu\text{m}$ and $kl=76$ for the data in a, and $l=0.17 \mu\text{m}$ resulting in $kl\approx 1.5$ for the data in b.

[中文](#)

To observe a possible localization transition, we have measured the

transmission coefficient as a function of sample thickness. In Fig. 4a, the transmission coefficient is shown for the coarse-grained powder. We see that the transmission behaves completely classically with $l=9.8\text{ }\mu\text{m}$, which is consistent with the coherent backscattering data. At very large sample thicknesses ($L>500\text{ }\mu\text{m}$), the transmission decreased more rapidly than linear due to the onset of absorption. This gives an upper limit for κ (defined as $\kappa=l_{\text{in}}^{-1}$) for the coarse-grained powder, of $\sim 0.13\text{ cm}^{-1}$, which shows again that the grinding process did not introduce any absorption. 中文

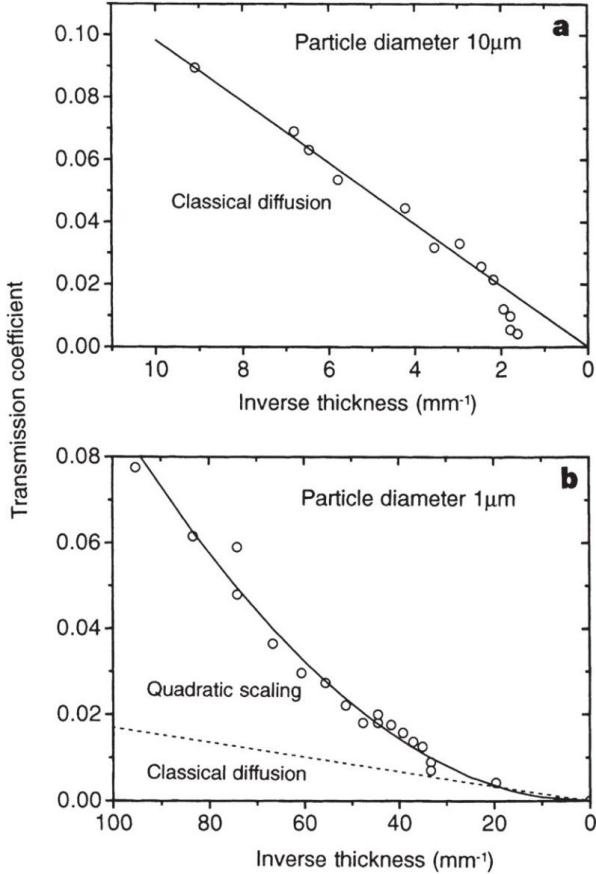


Fig. 4. Comparison of the transmission coefficients for two GaAs powders with different average particle diameters. Here the transmission coefficient is defined as the ratio between total transmitted flux and the incident flux. The total transmission is measured with an integrating sphere placed in contact with the back of the sample. The light source is as in Fig. 3, with beam diameter 0.5 mm and incident power 20 μW . The data in a correspond to particle a diameter of 10 μm and behave completely classically. The solid line is $T=l/L$, with

$l=9.8\text{ }\mu\text{m}$, which is in agreement with the backscattering data. The data in **b** correspond to a particle diameter of $\sim 1\text{ }\mu\text{m}$. The dashed line is the theoretical curve for classical diffusion with $l=0.17\text{ }\mu\text{m}$, as obtained from the backscattering data. The solid line is a quadratic fit to the data. This quadratic dependence of the transmission coefficient on the inverse thickness is the expected behaviour at an Anderson localization transition. [中文](#)

In Fig. 4b, the transmission coefficient T is shown for the fine-grained powder. The dashed line is the theoretical curve for classical diffusion assuming $l=0.17\text{ }\mu\text{m}$ as obtained from the backscattering data. Whereas for classical diffusion T would decrease linearly with the sample thickness L , we find for these samples a quadratic dependence ($T\propto L^{-2}$). This is exactly the behaviour predicted by the scaling theory of localization at the localization transition^{12,18}. We note that no classical diffusion process can show a quadratic system-size dependence. [中文](#)

If we decrease the particle size even further we expect (from Mie-scattering theory) to obtain even stronger scattering. In Fig. 5, the transmission coefficient is shown for a powder with an average particle diameter of 300 nm. In Fig. 5b we see that the quadratic behaviour has changed into an exponential decay in this case, as expected in the localized regime. The transport of light has come to a halt owing to interference, and the system has made a phase transition from a conducting into a localized state. The characteristic length scale for the exponential decay is called the localization length, which here is $4.3\text{ }\mu\text{m}$. [中文](#)

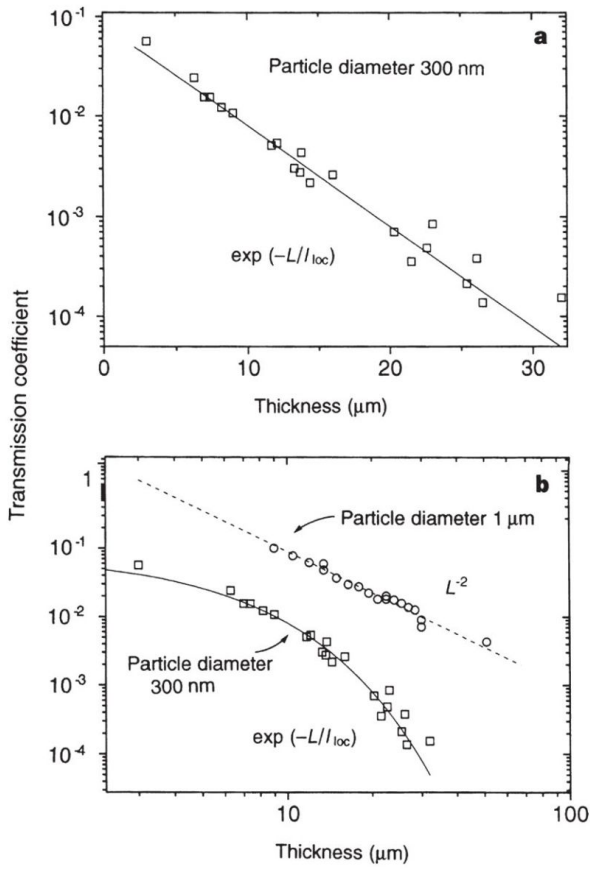


Fig. 5. The transmission coefficient of very fine GaAs powder as a function of thickness. The average particle diameter is 300 nm. In **a**, the data are plotted on a semi-logarithmic scale. The solid line is an exponential fit $\exp(-L/l_{\text{loc}})$ with a localization length of $l_{\text{loc}} = 4.3 \mu\text{m}$. In **b**, the same data are plotted on a double-logarithmic scale and the data of Fig. 4b are imported for comparison. We see that for the very fine powder, the quadratic behaviour changes to an exponential decay. The system goes into a localized state where it behaves as a (non-absorbing) insulator. [中文](#)

Different techniques could be used to map out the complete localization transition. The amount of scattering could be varied by changing the average particle diameter, the refractive index contrast, the particle density and the wavelength of the light. An important experiment would be a time-resolved transmission experiment in which the reduction of the diffusion constant at the Anderson localization transition is observed. Localization of classical waves is, in many ways, similar to Anderson localization of electrons. There are,

however, also interesting differences between light and electrons. For experiments with light waves, coherent (laser) sources are available; the wavelength of such sources may be easily adjusted. Furthermore, for electromagnetic waves photon–photon interactions can be neglected, whereas in the case of electrons, electron–electron interactions always play a role. This latter property in particular makes light in strongly disordered media an interesting system in which to study the Anderson localization transition. 中文

(390, 671-673; 1997)

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Received 16 June; accepted 15 October 1997.

References:

1. Anderson, P. W. Absence of diffusion in certain random lattices. *Phys. Rev.* **109**, 1492-1505 (1958).
2. Bergmann, G. Quantitative analysis of weak localization in thin Mg films by electroresistance measurements. *Phys. Rev. B* **25**, 2937-2939 (1982).
3. Altshuler, B. L., Aronov, A. G., Khmel'nitskii, D. E. & Larkin, A. I. in *Quantum Theory of Solids* (ed. Lifshits, I. M.) 130-237 (MIR, Moscow, 1983).
4. Khmel'nitskii, D. E. Localization and coherent scattering of electrons. *Physica B* **126**, 235-241 (1984).
5. Lee, P. A. & Ramakrishnan, T. V. Disordered electronic systems. *Rev. Mod. Phys.* **57**, 287-337 (1985).
6. Condat, C. A., Kirkpatrick, T. R. & Cohen, S. M. Acoustic localization in one dimension in the presence of a flow field. *Phys. Rev. B* **35**, 4653-4661 (1987).
7. Souillard, B. in *Chance and Matter* (eds Souletie, J., Vannimenus, J. & Stora, R.) Ch. 5 (North-Holland, Amsterdam, 1987).
8. Ando, T. & Fukuyama, H. (eds) *Anderson Localization, Springer Proceedings in Physics* Vol. 28 (Springer, Berlin, 1988).
9. Vollhardt, D. & Wölfle, P. in *Electronic Phase Transitions* (eds Hanke, W. & Kopaev, Yu. V.) 1-78 (Elsevier, Amsterdam, 1992).
10. Sheng, P. *Introduction to Wave Scattering, Localization, and Mesoscopic Phenomena* (Academic, San Diego, 1995).
11. John, S. Electromagnetic absorption in a disordered medium near a photon mobility edge. *Phys. Rev. Lett.* **53**, 2169-2172 (1984).

12. Anderson, P. W. The question of classical localization: a theory of white paint? *Phil. Mag. B* **52**, 505-509 (1985).
13. Sheng, P. & Zhang, Z.-Q. Scalar-wave localization in a two-component composite. *Phys. Rev. Lett.* **57**, 1879-1882 (1986).
14. Arya, K., Su, Z. B. & Birman, J. L. Anderson localization of electromagnetic waves in a dielectric medium of randomly distributed metal particles. *Phys. Rev. Lett.* **57**, 2725-2728 (1986).
15. Lagendijk, A., van Albada, M. P. & van der Mark, M. B. Localization of light: the quest for the white hole. *Physica A* **140**, 183-190 (1986).
16. Kaveh, M. Localization of photons in disordered systems. *Phil. Mag. B* **56**, 693-703 (1987).
17. Soukoulis, C. M., Economou, E. N., Grest, G. S. & Cohen, M. H. Existence of Anderson localization of classical waves in a random two-component medium. *Phys. Rev. Lett.* **62**, 575-578 (1989).
18. Abrahams, E., Anderson, P. W., Licciardello, D. C. & Ramakrishnan, T. V. Scaling theory of localization: absence of quantum diffusion in two dimensions. *Phys. Rev. Lett.* **42**, 673-676 (1979).
19. Mott, N. F. *Metal-Insulator Transitions* (Taylor & Francis, London, 1974).
20. Dalichaouch, R., Armstrong, J. P., Schultz, S., Platzman, P. M. & McCall, S. L. Microwave localization by two-dimensional random scattering. *Nature* **354**, 53-55 (1991).
21. Garcia, N. & Genack, A. Z. Anomalous photon diffusion at the threshold of the Anderson localization transition. *Phys. Rev. Lett.* **66**, 1850-1853 (1991).
22. Genack, A. Z. & Garcia, N. Observation of photon localization in a three-dimensional disordered system. *Phys. Rev. Lett.* **66**, 2064-2067 (1991).
23. Kuga, Y. & Ishimaru, J. Retroflection of a dense distribution of spherical particles. *J. Opt. Soc. Am. A* **1**, 831-835 (1984).
24. Albada, M. P. & Lagendijk, A. Observation of weak localization of light in a random medium. *Phys. Rev. Lett.* **55**, 2692-2695 (1985).
25. Wolf, P. E. & Maret, G. Weak localization and coherent backscattering of photons in disordered media. *Phys. Rev. Lett.* **55**, 2696-2699 (1985).
26. Mark, M. B., Albada, M. P. & Lagendijk, A. Light scattering in strongly scattering media: multiple scattering and weak localization. *Phys. Rev. B* **37**, 3575-3592 (1988).
27. Akkermans, E., Wolf, P. E., Maynard, R. & Maret, G. Theoretical study of the coherent backscattering of light by disordered media. *J. Phys. (Paris)* **49**, 77-98 (1988).
28. Edrei, I. & Stephen, M. J. Optical coherent backscattering and transmission in a disordered media near the mobility edge. *Phys. Rev. B* **42**, 110-117 (1990).
29. Zhu, J. X., Pine, D. J. & Weitz, D. A. Internal reflection of diffusive light in random media. *Phys. Rev. A* **44**, 3948-3957 (1991).
30. Wiersma, D. S., Albada, M. P., van Tiggelen, B. A. & Lagendijk, A. Experimental evidence for recurrent multiple scattering events of light in disordered media. *Phys. Rev. Lett.* **74**, 4193-4196 (1995).

Acknowledgements. We thank F. Bogani, M. Colocci, R. Torre and M. Gurioli for discussions, and M. Colocci also for supplying GaAs crystals. D.S.W. thanks M. van Albada for advice and

continuous support during the experiments, and M. Brugmans for reading of the manuscript. A.L. was supported by the “Stichting voor Fundamenteel Onderzoek der Materie” (FOM). This work was supported by the Commission of the European Community.

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无序介质中光的局域化

维尔斯马等

量子物理学指出，在材料的无序程度足够显著的情况下，粒子在该材料中的扩散会被波的相消干涉所抑制。这种强烈的局域化现象，或者叫“安德森局域化”（因为该现象最早是由物理学家菲利普·安德森描述出来的），影响了电子在多种固体中的行为，而且也会影响光子的行为。在本文中，迪德里克·维尔斯马和他的同事们用实验证实了光在半导体粉末中的安德森局域化。他们研究了光在砷化镓晶体中和在具有不同粒度的几种砷化镓粉末中的透射。他们发现，光透射率在某一粒度值处出现一个显著的阈值，在该处，无序诱导的局域化完全阻挡了光的透射，导致样品的透射系数随样品厚度呈指数下降而非线性下降。

[英文](#)

安德森局域化^[1]现象是科学家预测到的无序材料不同寻常的传输性质之一。这是一种由无序环境诱导产生的电子传输行为上的相变，表现为由经典的扩散向局域态的转变，而经典扩散是众所周知的欧姆定律适用的范围，局域态则对应绝缘体材料。这个效应来源于被固体中的缺陷多次散射的电子之间的干涉^[2-10]。可以预料的是，电磁波的多次散射会产生相似的现象，但是有一个重要的简化：和电子不同，光子之间不会有相互作用。这使光子在无序材料中的传输成为研究安德森局域化的理想模型^[10-17]。在本文中，利用基于强散射性半导体粉末的光学实验，我们报道了光的安德森局域化的直接实验证据。

[英文](#)

光的多次散射是生活中常见的现象，会出现在例如糖、雾、白色颜料、云中。光在这些介质中的传播通常可以用标准扩散过程来描述。对

于光在无序材料中的扩散，欧姆定律依然适用，如同电子在电阻器中的扩散一样，即传导性随系统长度（厚度）线性下降。[英文](#)

安德森局域化使经典扩散不再适用。也就是说，一旦散射量高于某一临界值，材料就出现局域态（见图1）。观察这种变化的最佳方式是测试系统的透射。在局域态中，透射系数随样品厚度呈指数减小，而非呈线性减小。转变过程中，透射系数预计会与厚度的倒数呈幂律相关，且很有可能是二次幂律^[12,18]。[英文](#)

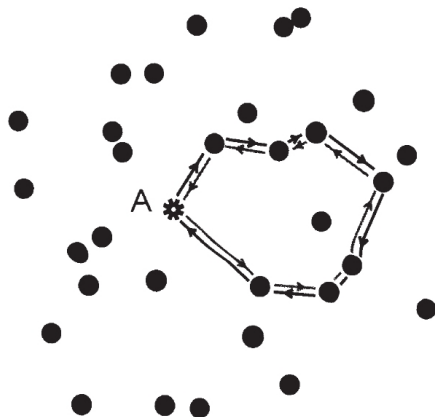


图1．无序系统中波的和德森局域化来源于多次弹性散射的干涉。在这里我们把无序介质中的A点看作是一个光源（好比一个受激原子发射出一个光子）。这个光源用星号标记，而圆点表示散射点。一条能返回到光源的不规则光路可以从相反的两个方向去实现。这两支沿着这条回路反向传播的波会具有相同的相位，从而在A点形成相长干涉。这种情况导致波回到A点的概率增加而向远离A点方向传播的概率减小。一旦平均自由程 l 减小，出现这种回路的概率就增加了，并且在散射足够强的情况下，干涉会导致系统发生由普通传导态到局域态的相变。在局域区，系统表现为无吸收的光绝缘体。例如，照在一块平板上的光几乎都会被反射，仅剩的一点透射光会随板的厚度呈指数衰减。[英文](#)

探寻光的局域化的最大难点在于实现足够强的散射。衡量散射量最恰当的方法是用光在介质中的平均自由程 l 乘以波矢量 k 的大小。局域化发生的条件为 $kl \leq 1$ （参考文献19），即（修正的）Ioffe–Regel判据。如果能意识到，低于 $kl=1$ 时，在波被再次散射前电场不能完成一次振荡，我们便能直观地理解这条判据。迄今为止，对局域化效应的报告仅限于二维棒状系统中的微波^[20]和封闭空间（充满金属和电介质球的铜管）里的微波^[21,22]。在后者中，微波被大量吸收，导致数据解释变得复杂。和光波实验比起来，微波实验的劣势在于吸收难以避免。[英文](#)

我们已利用半导体粉末实现光波的强散射。半导体可以具有很大的折射率，而对于带隙中的波长来说，吸收是极小的。我们使用波长 $\lambda = 1,064 \text{ nm}$ 的光，在这个波长下纯砷化镓的吸收系数 $\kappa \ll 1 \text{ cm}^{-1}$ ，折射率为3.48。我们的样品由纯的（99.999%）砷化镓（GaAs）晶体构成，是在陶瓷研钵里手动碾磨（以悬浮于甲醇的形式）以及在微型行星式高能球磨机中低速碾磨而成的。通过改变碾磨时间，我们得到了具有不同平均粒度从而具有不同散射量的样品。碾磨半导体时，操作人员必须非常小心，以确保实验中所用波长的光不会被吸收。对于粉末来说，表面态更为重要，并且碾磨过程（即使只用了很小的力）会引起应变或晶格形变。表面态、应变和晶格形变都会导致带边出现吸收带尾。通过测量透射率与温度的相关性，我们描绘了材料的带边变化（图2）。

英文

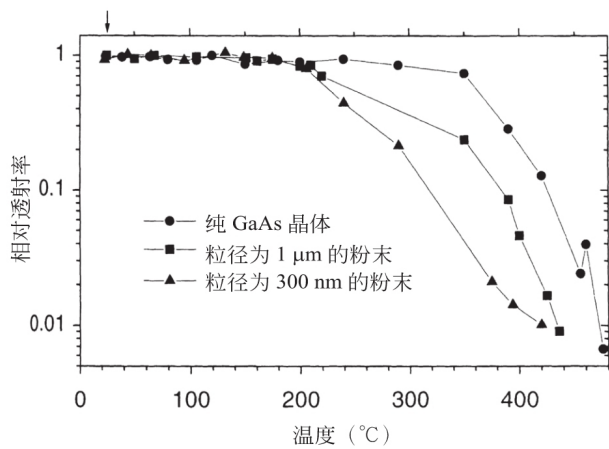


图2. 纯GaAs晶体与粉末之间透射率与温度相关性的对比。图中展示了粒径为1 μm和300 nm的数据。粉末样品的透射率是在一个特定的厚度下测得的，即室温下总透射率为1%时的厚度。所有曲线都被按比例缩放，使得最高点是1。一旦温度 T 升高，带隙就移向低能量 $E_g(T)$ ，对应于高波长 $\lambda_g = 1.24/E_g$ （单位是μm）。和温度的相关性满足经验关系： $E_g(T) = E_g(0) - \alpha T^2 / (T + \beta)$ ，其中（GaAs的） $E_g(0) = 1.522$ ， $\alpha = 8.871 \times 10^{-4}$ ， $\beta = 572$ ， T 的单位是K。这种依赖于温度的移动，使在不改变激光波长的情况下，遍历带隙中激光波长附近的能量成为可能。例如，200 °C的温度对应于65 nm的波长改变量。左上角的箭头指出了我们其余全部实验的操作温度。我们注意到，在GaAs晶体被碾磨得更细的时候，吸收带边缘变得没那么陡直了；这很可能是因为表面态和晶格形变的影响加重了。但是激光波长附近的波长区域仍然没有吸收。

英文

从图2中我们发现，在碾磨得更细的时候，吸收带边缘变得没那么陡直了，而且吸收的起始点移入带隙中了。然而另一个明确的方面是，

吸收带尾所处的波长区域远比我们使用的激光的波长要小（65 nm），这样就保证了这种带尾不会使我们的实验里出现激光的吸收。 [英文](#)

为确定此材料中的平均自由程 l ，我们应用了相干背散射。该现象是反向传播的波之间的普通干涉效应，使背散射谱图上出现一个窄的锥形[23]。这被看作是安德森局域化的前身，也因此被称为“光的弱局域化”[24,25]。背散射的锥形的宽度和尖端的角度都与 l 成反比（参考文献26和27），从而使确定样品中的散射量成为可能。而且，尖端是由（理论上）无限长的光程得到的，所以只在没有吸收的情况下出现[26-28]。图3中，我们展示了粗粒粉末（图3a）和细粒粉末（图3b）的背散射锥形，粉末的平均粒径分别为10 μm 和1 μm 。从尖端的角度中我们发现，粗粒粉末中 $l=8.5 \mu\text{m}$ ，所以 $kl=76$ ，细粒粉末中 $l\approx 0.17 \mu\text{m}$ ，所以 $kl\approx 1.5$ 。观测值 $kl=1.5$ 是迄今报道过的光波的最小 kl 值的四分之一[30]。无论从实验角度还是理论角度来看，向局域化转化的过程中，相干背散射锥的形状都很有趣，这一点会在别处讨论。 [英文](#)

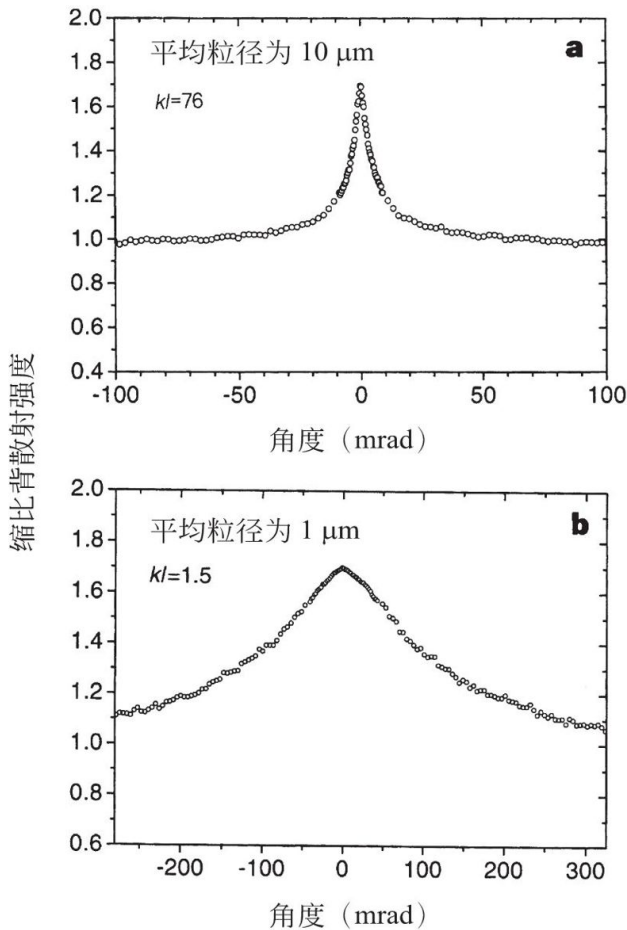


图3. 从粗粒 (a) 和细粒 (b) GaAs粉末中得到的相干背散射锥。两种样品都有很大的多分散性，平均粒径分别为10 μm 和1 μm 。用来照射样品的是锁模Nd:YAG激光，频率为76 MHz，波长为1,064 nm，脉冲宽度为100 ps，光束直径为6 mm，入射功率为100 mW。在全部实验中，我们都避免了非线性吸收（如双光子吸收）。方法是把入射功率降低到20 mW后发现功率的降低并没有影响实验结果。检测是在保偏通道中进行的。平均自由程由锥形尖端的角度计算得出[27]，内反射也被考虑在内[29]。图a中数据得出的结果是 $l = 8.5 \mu\text{m}$ ， $kl = 76$ ，图b则是 $l = 0.17 \mu\text{m}$ ， $kl \approx 1.5$ 。 [英文](#)

为了观测到一个可能的向局域化转化的过程，我们测量了透射系数随样品厚度的变化。图4a展示了粗粒粉末的透射系数。可以看出，这种透射完全表现为经典扩散，其中 $l = 9.8 \mu\text{m}$ ，与相干背散射得到的数据一致。在样品厚度特别大的时候 ($L > 500 \mu\text{m}$)，由于吸收的出现，透射率的降低速度会超线性。因此粗粒粉末的 κ 值（定义为 $\kappa = l_{\text{in}}^{-1}$ ）存在上限，约为 0.13 cm^{-1} ，再次说明了碾磨过程不会引入吸收。 [英文](#)

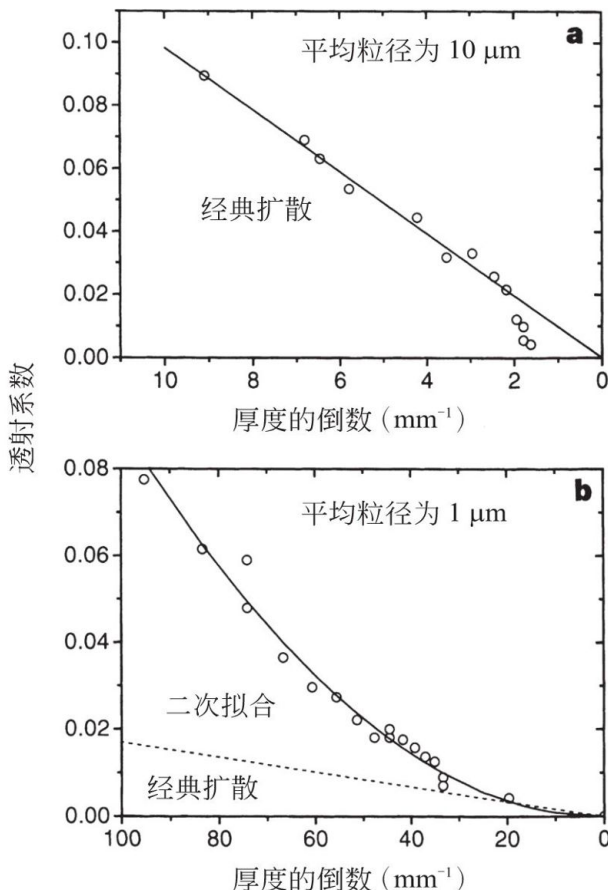


图4．平均粒径不同的两种GaAs粉末透射系数的对比。此处，透射系数被定义为总透射通量与入射通量之比。总透射量是由紧贴样品背面的积分球测出的。光源和图3中的一样，光束直径为0.5 mm，发射功率为20 μW 。图a中的数据来自直径为10 μm 的颗粒，完全表现为经典扩散。实线为 $T = l/L$ ，其中 $l = 9.8\ \mu\text{m}$ ，这和背散射数据相符。图b中的数据对应粒径约1 μm 的情况。虚线是按经典扩散作出的理论曲线，其中 $l = 0.17\ \mu\text{m}$ ，由背散射数据所得。实线是实验数据的二次拟合。在转变为安德森局域化的过程中，透射系数与厚度的倒数的二次相关符合预期。 英文

图4b展示了细粒粉末的透射系数 T 。虚线是根据经典扩散画出的理论曲线，其中假设 $l = 0.17\ \mu\text{m}$ ，即由背散射数据算出的值。虽然经典扩散中的 T 值会随样品厚度 L 的增大呈线性下降，但我们发现这些样品中出现了二次相关 ($T \propto L^{-2}$)。这和以局域化标度理论预测出的向局域化转化的表现完全一致^[12,18]。我们在此特别指出，任何经典扩散过程都不会呈现与系统尺度的二次相关。 英文

如果我们继续降低粒度，我们会（根据米氏散射理论）得到更强的

散射。图5给出了一种平均粒径为300 nm的粉末的透射系数。从图5b中我们可以看出，在这种情况下二次相关已经变为指数衰减，符合局域区的预期。由于干涉，光不再透射，系统实现了由传导态到局域态的相变。指数衰减的特征长度尺度被称为局域化长度，此处为4.3 μm 。

英文

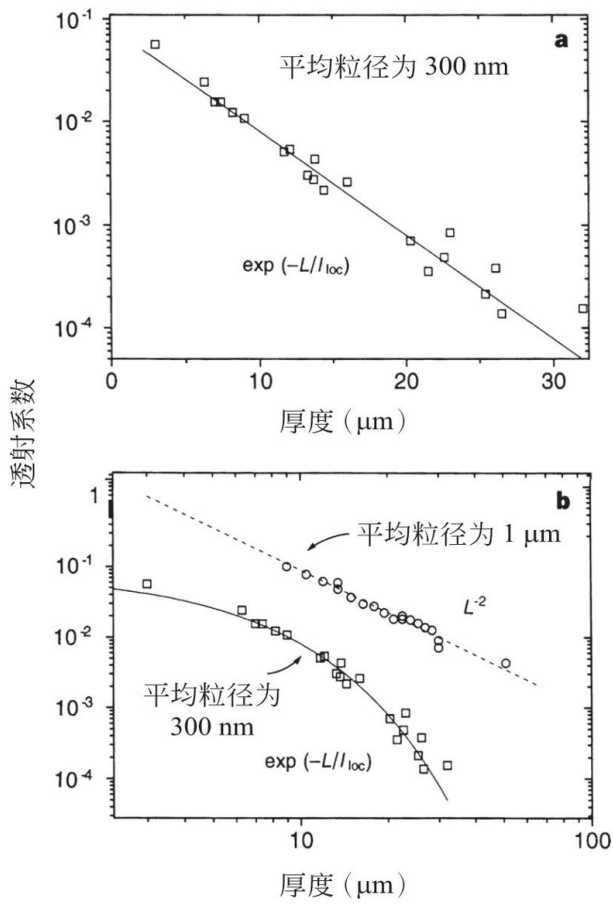


图5．极细GaAs粉末的透射系数与厚度的关系。平均粒径为300 nm。图a中，数据被标在半对数坐标中。实线是指数化拟合曲线 $\exp(-L/l_{\text{loc}})$ ，其中局域化长度 $l_{\text{loc}}=4.3\ \mu\text{m}$ 。图b中，同样的数据被标在双对数坐标中，与图4b中的数做比较。我们可以看出，在极细的粉末中，二次相关变成了指数衰减。系统变为局域态，即表现为（无吸收的）光绝缘体。 [英文](#)

多种方法可以用来描绘完整的向局域化转化的过程。通过改变平均粒径、折射率对比度、颗粒密度以及光的波长，可以改变散射量。时间分辨透射实验是一种重要的实验，在该种实验中，向安德森局域化转化的过程中，扩散常数的减小是可观测到的。经典波的局域化在很多方面

都类似于电子的安德森局域化。然而，光和电子有一些有趣的不同点。在光波实验中，相干（激光）光源是可实现的；这种光源的波长是很容易调节的。而且，电磁波中的光子-光子相互作用可以忽略不计，但是电子体系中的电子-电子相互作用总是对实验有影响。后者这种特性使在强无序介质中的光成为一个研究安德森局域化转变的有趣系统。

英文

（葛聆飒 翻译；翟天瑞 审稿）

Extraordinary Optical Transmission through Sub-wavelength Hole Arrays

T. W. Ebbesen *et al.*

Light rays are generally considered to be blocked by apertures smaller than the light's wavelength. This limits the resolution of optical microscopes. But here Thomas Ebbesen of the NEC Corporation in Princeton and colleagues report the surprising ability of light to “squeeze through” an array of sub-wavelength-sized holes in a thin metal sheet. The effect stems from the interaction of light with mobile electrons on the surface of the metal, which can be excited into wavelike motions called plasmons. A plasmon wave can pass through the hole and then re-radiate light on the far side. This paper stimulated interest in the topic now called plasmonics, which takes advantage of light-plasmon applications to achieve a range of unusual effects, including “invisibility shields”. [中文](#)

The desire to use and control photons in a manner analogous to the control of electrons in solids has inspired great interest in such topics as the localization of light, microcavity quantum electrodynamics and near-field optics¹⁻⁶. A fundamental constraint in manipulating light is the extremely low transmittivity of apertures smaller than the wavelength of the incident photon. While

exploring the optical properties of submicrometre cylindrical cavities in metallic films, we have found that arrays of such holes display highly unusual zero-order transmission spectra (where the incident and detected light are collinear) at wavelengths larger than the array period, beyond which no diffraction occurs. In particular, sharp peaks in transmission are observed at wavelengths as large as ten times the diameter of the cylinders. At these maxima the transmission efficiency can exceed unity (when normalized to the area of the holes), which is orders of magnitude greater than predicted by standard aperture theory. Our experiments provide evidence that these unusual optical properties are due to the coupling of light with plasmons—electronic excitations—on the surface of the periodically patterned metal film. Measurements of transmission as a function of the incident light angle result in a photonic band diagram. These findings may find application in novel photonic devices. [中文](#)

A variety of two-dimensional arrays of cylindrical cavities in metallic films were prepared and analysed for this study. Typically, a silver film of thickness $t=0.2\text{ }\mu\text{m}$ was first deposited by evaporation on a quartz substrate. Arrays of cylindrical holes were fabricated through the film by sputtering using a Micrion focused-ion-beam (FIB) System 9500 (50 keV Ga ions, 5 nm nominal spot diameter). The individual hole diameter d was varied between 150 nm and $1\text{ }\mu\text{m}$ and the spacing between the holes (that is, the periodicity) a_0 , was between 0.6 and $1.8\text{ }\mu\text{m}$. The zero-order transmission spectra, where the incident and detected light are collinear, were recorded with a Cary 5 ultraviolet–near infrared spectrophotometer with an incoherent light source, but the arrays were also studied on an optical bench for transmission, diffraction and reflection properties using coherent sources. [中文](#)

Figure 1 shows a typical zero-order transmission spectrum for a square

array of 150 nm holes with a period a_0 of 0.9 μm in a 200 nm thick Ag film. The spectrum shows a number of distinct features. At wavelength $\lambda=326$ nm the narrow bulk silver plasmon peak is observed which disappears as the film becomes thicker. The most remarkable part is the set of peaks which become gradually stronger at longer wavelengths, increasingly so even beyond the minimum at the periodicity a_0 . There is an additional minimum at $\lambda = a_0 \sqrt{\epsilon}$ corresponding to the metal-quartz interface (where ϵ is the dielectric constant of the substrate). For $\lambda = a_0 \sqrt{\epsilon}$, there is no diffraction from the array nor from the individual holes. As expected, the first-order diffraction spots can be seen to be grazing the surface (that is, the diffraction angle approaches 90°) as the wavelength approaches the period from below (this might, in fact, enhance the coupling to be discussed in the next paragraphs). The maximum transmitted intensity occurs at 1,370 nm, nearly ten times the diameter of an individual hole in the array. Even more surprising is that the absolute transmission efficiency, calculated by dividing the fraction of light transmitted by the fraction of surface area occupied by the holes, is ≥ 2 at the maxima. In other words, more than twice as much light is transmitted as impinges directly on the holes. Furthermore, the transmittivity of the array scales linearly with the surface area of the holes. This is all the more remarkable considering that the transmission efficiency of a single sub-wavelength aperture is predicted by Bethe⁷ to scale as $(r / \lambda)^4$ where r is the hole radius; accordingly for a hole of 150 nm diameter one expects a transmission efficiency on the order of 10^{-3} . In addition, the intensity (I) of the zero-order transmission from a grating is expected to decrease monotonically at larger wavelengths ($I \propto \lambda^{-1}$) (ref. 8). Therefore our results must imply that the array itself is an active element, not just a passive geometrical object in the path of the incident beam. 中文

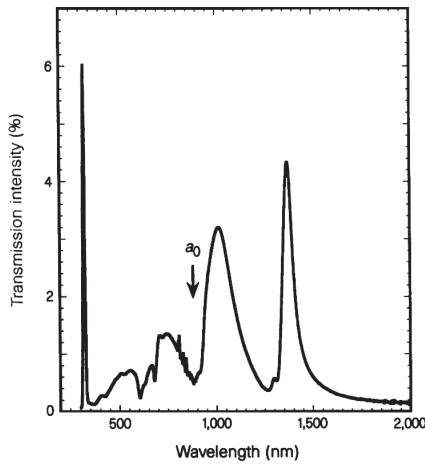


Fig. 1. Zero-order transmission spectrum of an Ag array ($a_0=0.9\text{ }\mu\text{m}$, $d=150\text{ nm}$, $t=200\text{ nm}$).

[中文](#)

To understand the origin of this phenomenon, we tested the dependence on all the possible variables such as hole diameter, periodicity, thickness and type of metal. It is beyond the scope of this Letter to describe the details of all these experiments. Instead we summarize our observations and illustrate some of the key factors that determine the shape of these spectra. To begin with, the periodicity of the array determines the position of the peaks. The positions of the maxima scale exactly with the periodicity, as shown in Fig. 2a, independent of metal (Ag, Cr, Au), hole diameter and film thickness. The width of the peaks appears to be strongly dependent on the aspect ratio (t/d or depth divided by diameter) of the cylindrical holes (Fig. 2a). For $t/d=0.2$, the peaks are very broad and just discernible and when the ratio reaches ~ 1 , the maximum sharpness is obtained. Further narrowing might depend on the quality of the individual holes. The thickness dependence of the spectra is displayed in Fig. 2b for 0.2 and 0.5 μm Ag films. While the intensity of the bulk plasmon peak decreases rapidly in this range, that of the longer-wavelength peaks decreases approximately linearly with thickness. The spectra change significantly with the type of lattice, for example whether the array is a square or a triangular lattice. [中文](#)

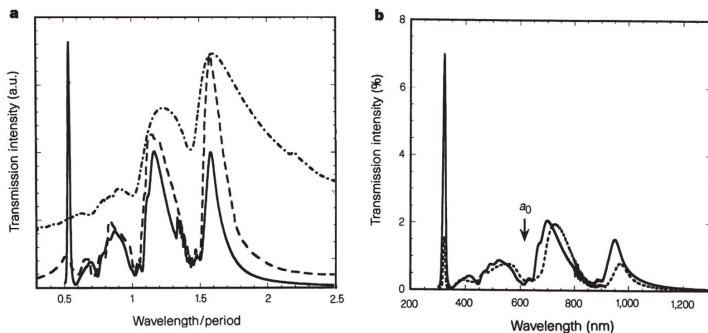


Fig. 2. Effects of parameters on zero-order transmission spectra. **a**, Spectra for various square arrays as a function of λ / a_0 . Solid line: Ag, $a_0=0.6 \mu\text{m}$, $d=150 \text{ nm}$, $t=200 \text{ nm}$; dashed line: Au, $a_0=1.0 \mu\text{m}$, $d=350 \text{ nm}$, $t=300 \text{ nm}$; dashed-dotted line: Cr, $a_0=1.0 \mu\text{m}$, $d=500 \text{ nm}$, $t=100 \text{ nm}$. **b**, Spectra for two identical Ag arrays with different thicknesses. Solid line: $t=200 \text{ nm}$; dashed line: $t=500 \text{ nm}$ (this spectrum has been multiplied by 1.75 for comparison). For both arrays: $a_0=0.6 \mu\text{m}$; $d=150 \text{ nm}$. 中文

Two important clues relating this phenomenon to surface plasmons (SPs) come from the following observations. One is the absence of enhanced transmission in hole arrays fabricated in Ge films which points to the importance of the metallic film. The other clue is the angular dependence of the spectra in metallic samples. The zero-order transmission spectra change in a marked way even for very small angles, as illustrated in Fig. 3 where the spectra were recorded every 2° . The peaks change in intensity and split into new peaks which move in opposite directions. This is exactly the behaviour observed when light couples with SPs in reflection gratings⁹⁻¹⁴. SPs are oscillations of surface charges at the metal interface and are excited when their momentum matches the momentum of the incident photon and the grating as follows:

$$k_{\text{sp}} = k_x \pm nG_x \pm mG_y$$

where k_{sp} is the surface plasmon wavevector, $k_x = (2\pi / \lambda) \sin\theta$ is the component of the incident photon's wavevector in the plane of the grating and $G_x = G_y = 2\pi / a_0$ are the grating momentum wavevectors for a square array. Therefore if the angle of incidence θ is varied, the incident radiation excites different SP modes and by recording the

peak energies as a function of k_x we obtain the dispersion relation shown in Fig. 4. This figure reveals the band structure of SP in the two-dimensional array and it clearly demonstrates the presence of gaps with energies around 30 to 50 meV; these are due to the lifting of the degeneracy by SPs interacting with the lattice. An extrapolation of the dispersion curves yields an intercept with the k -axis at a value which is within the experimental error ($\sim 10\%$) of that expected from the periodicity ($2\pi / a_0$). The results of Figs 3 and 4 are also sensitive to polarization as expected, but a clear assignment has not yet been possible because of inherent structure of the grains in the metal film.

中文

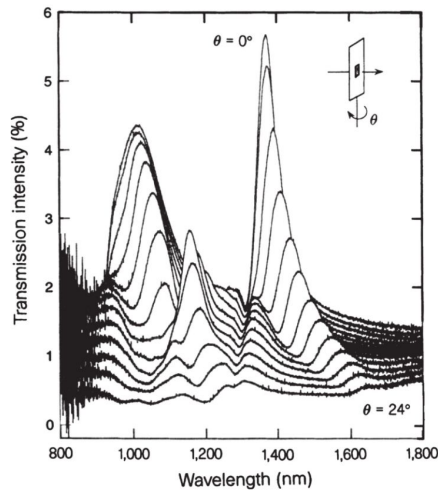


Fig. 3. Zero-order transmission spectra as a function of incident angle of the light. Spectra were taken every 2° up to 24° for a square Ag array ($a_0=0.9\text{ }\mu\text{m}$, $d=150\text{ nm}$, $t=200\text{ nm}$). The individual spectra are offset vertically by 0.1% from one another for clarity.

中文

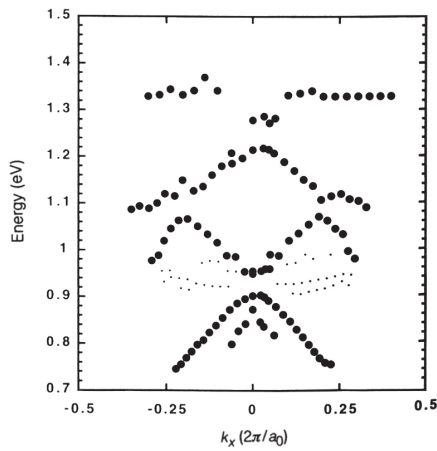


Fig. 4. Dispersion curves (solid circles) along the [10] direction of the array. These curves are extracted from the energy of the transmission peaks of Fig. 3. The momentum k_x is in the plane of the array and is given by $k_x = (2\pi / \lambda) \sin\theta$ where θ is the incident angle of the beam (the units are normalized to $2\pi / a_0$). The curves with the smaller dots correspond to peaks whose amplitudes are much weaker and may or may not be related to the band structure as they do not shift significantly with momentum. 中文

In our experiments the coupling of light with SPs is observed in transmission rather than reflection, in contrast with previous work on SPs on reflection gratings. In those studies the coupling of light to SPs is observed as a redistribution of intensity between different diffracted orders. Even in transmission studies of wire gratings by Lochbihler¹⁵, the effect of SPs is observed through dips in zero-order transmitted light. There is an extensive literature on the infrared properties of wire grids which show a broad transmission centred at $\lambda \approx 1.2a_0$; this has been interpreted in terms of induction effects, in analogy with electric circuits^{16,17}. Our results demonstrate the strong enhancement of transmitted light due to coupling of the light with the SP of the two-dimensional array of sub-wavelength holes. Furthermore our results indicate a number of unique features that cannot be explained with existing theories. The SP modes on the metal–air interface are distinctly different from those at the metal–quartz interface. However, the spectra are identical regardless of whether the sample is illuminated from the metal or quartz side. At present we do not understand the detailed mechanism of the coupling between the SP on

the front and back surfaces which results in larger than unity transmission efficiency of the holes. The thickness dependence (see Fig. 2b) suggests that the holes play an important part in mediating this coupling and that nonradiative SP modes are transferred to radiative modes by strong scattering in the holes. 中文

In photonic bandgap arrays^{2,4}, the material is passive and translucent at all wavelengths except at the energies within the gap. In the present arrays, the material plays an active role (through the plasmons) and it is opaque at all wavelengths except those for which coupling occurs. The combination, or integration, of these two types of phenomena might lead to optical features that are very interesting from both fundamental and technological points of view. The demonstration of efficient light transmission through holes much smaller than the wavelength and beyond the inter-hole diffraction limit might, for example, inspire designs for novel nearfield scanning optical microscopes⁶, or sub-wavelength photolithography. Theoretical analysis of the results would also be useful for gaining better insight into this extraordinary transmission phenomenon. Perhaps only then can we expect to grasp the full implications of these findings. 中文

(391, 667-669; 1998)

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Received 15 July; accepted 24 November 1997.

References:

1. John, S. Localization of light. *Phys. Today* 32 (May 1991).
2. Yablonovitch, E. & Leung, K. M. Hope for photonic bandgaps. *Nature* **351**, 278 (1991).
3. Dalichaouch, R., Armstrong, J. P., Schultz, S., Platzman, P. M. & McCall, S. L. Microwave localization by two-dimensional random scattering. *Nature* **354**, 53-55 (1991).

4. J. D. Joannopoulos, Meade R. D. & Winn, J. N. *Photonic Crystals* (Princeton Univ. Press, Princeton, 1995).
5. Haroche, S. & Kleppner, D. Cavity quantum electrodynamics. *Phys. Today* **24** (January 1989).
6. Betzig, E. & Trautman, J. K. Near-field optics: Microscopy, spectroscopy, and surface modification beyond the diffraction limit. *Science* **257**, 189-194 (1992).
7. Bethe, H. A. Theory of diffraction by small holes. *Phys. Rev.* **66**, 163-182 (1944).
8. Born, M. & Wolf, E. *Principles of Optics* (Pergamon, Oxford, 1980).
9. Ritchie, R. H., Arakawa, E. T., Cowan, J. J. & Hamm, R. N. Surface-plasmon resonance effect in grating diffraction. *Phys. Rev. Lett.* **21**, 1530-1533 (1968).
10. Raether, H. *Surface Plasmons* (Springer, Berlin, 1988).
11. Chen, Y. J., Koteles, E. S., Seymour, R. J., Sonek, G. J. & Ballantyne, J. M. Surface plasmons on gratings: coupling in the minigap regions. *Solid State Commun.* **46**, 95-99 (1983).
12. Kitson, S. C., Barnes, W. L. & Sambles, J. R. Full photonic band gap for surface modes in the visible. *Phys. Rev. Lett.* **77**, 2670-2673 (1996).
13. Watts, R. A., Harris, J. B., Hibbins, A. P., Preist, T. W. & Sambles, J. R. Optical excitations of surface plasmon polaritons on 90 and 60 bi-gratings. *J. Mod. Opt.* **43**, 1351-1360 (1996).
14. Derrick, G. H., McPhedran, R. C., Maystre, D. & Neviere, M. Crossed gratings: a theory and its applications. *Appl. Phys.* **18**, 39-52 (1979).
15. Lochbihler, H. Surface polaritons on gold-wire gratings. *Phys. Rev. B* **50**, 4795-4801 (1994).
16. Ulrich, R. Far-infrared properties of metallic mesh and its complimentary structure. *Infrared Phys.* **7**, 37-55 (1967).
17. Larsen, T. A survey of the theory of wire grids. *I.R.E. Trans. Microwave Theory Techniques* **10**, 191-201 (1962).

Acknowledgements. We thank S. Kishida, G. Bugmann and J. Giordmaine for their encouragement, and R. Linke, R. McDonald, M. Treacy, J. Chadi and C. Tsai for discussions. We also thank G. Lewen, G. Seidler, A. Krishnan, A. Schertel, A. Dziesiaty and H. Zimmermann for assistance.

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通过亚波长孔洞阵列的超常光透射现象

埃贝森等

一般认为，当孔径小于光束波长时，光线将被阻碍，从而使光学显微镜的分辨率受到限制。但在本文中，普林斯顿日本电气公司研究所的托马斯·埃贝森及其同事报道了光具有“挤过”金属薄膜中亚波长尺寸孔洞阵列的惊人能力。该效应源于光与金属表面可迁移电子间的相互作用，使其激发成为与等离子体激元类似的波的运动。等离子体激元波可以通过孔洞，进而在远端发生光的再辐射。本文诱发了对目前名为等离子体光子学领域的兴趣，该领域旨在利用光—等离子体激元来实现包括“隐形盾”在内的一系列不寻常的效应。

[英文](#)

通过与控制固体中电子类似的方式来应用和控制光子的愿望，激起了人们对于光定域化、微腔量子电动力学和近场光学等主题的强大兴趣^[1-6]。调制光时遇到的基本限制就是当孔隙小于入射光子波长时透射率将非常低。但是，在探索金属薄膜中亚微米级圆柱形谐振腔的光学性质时，我们发现，当波长大于阵列周期时，这些孔洞阵列呈现出极不寻常的零级透射光谱（入射光与所探测的光二者共线），并且没有发生衍射。更为特别的是，在波长为圆柱直径的10倍处观测到尖锐的透射峰。而且在极大值处透射率可以超过1（按孔面积归一化后），这比标准孔隙理论的预期值高出几个数量级。我们的实验为下列说法提供了证据：这些不寻常的光学性质源自有周期性排列孔洞的金属薄膜表面上光与等离子体激元的耦合——电子激发作用。以透射作为光线入射角函数的观测获得了光子带图。这些发现可能会在新型光子器件中获得应用。

[英文](#)

在这项研究中，我们制备了具有多种二维阵列的圆柱形谐振腔的金属薄膜，并对实验结果进行了分析。典型的一例是，首先通过蒸镀在石英基质上沉积一层 $t=0.2\ \mu\text{m}$ 厚的银膜。继而用Micrion聚焦离子束系统9500（50 keV镓离子，5 nm标称点直径）进行溅镀，并在薄膜上加工出圆柱形孔洞阵列。单个孔直径 d 在150 nm到1 μm 之间，孔洞之间的距离 a_0 （亦即周期）则在0.6 μm 和1.8 μm 之间。零级透射光谱——其中入射光和所探测的光共线——是用一台具有非相干光源的Cary 5型紫外-近红外分光光度计记录的，也用相干光源对光具座上的阵列就透射、衍射和反射性质进行了研究。 英文

图1显示了在200 nm厚的银膜中，周期 a_0 为0.9 μm 的150 nm孔洞方形阵列典型零级透射光谱。光谱呈现出很多不同的特征。在波长 $\lambda=326\ \text{nm}$ 处可以看到本底银狭窄的等离子体峰，当薄膜厚度增加时它会消失。最值得关注的部分是在波长较长处逐渐变强的一组峰，甚至增加到超过位于周期 a_0 处的最小值。在 $\lambda=a_0\sqrt{\epsilon}$ 处有一个额外的最小值，它对应于金属-石英界面（其中 ϵ 是基质的介电常数）。在 $\lambda=a_0\sqrt{\epsilon}$ 处，阵列和单个孔洞都没有产生衍射。如同预期的那样，当波长由低处趋近周期值时，可以看到一级衍射点随之掠向表面（即衍射角接近 90° ）的现象（实际上，它可能增强我们在下面段落中将要讨论到的耦合作用）。最大透射强度出现在1,370 nm处，这一波长大约是阵列中单独一个孔洞的直径的10倍。更令人吃惊的是绝对透射率——由光的透射部分除以孔洞占据的表面积即可算出——在最大处 ≥ 2 。换句话说，透射出的光强比直接撞击孔洞的光强要高出一倍以上。此外，阵列的透射率随着孔洞表面积呈线性变化。如果考虑到贝特^[7]关于单个亚波长孔道透射率与 $(r/\lambda)^4$ 成比例的推断——其中 r 是孔洞半径，这一点就更加值得注意；据此推断，对于直径150 nm的孔洞来说，可以预期具有 10^{-3} 数量级的透射率。另外，预期光栅产生的零级透射强度（ I ）会在较大波长（ $I\propto\lambda^{-1}$ ）处单调地下降（参考文献8）。因此我们的结果必然意味着阵列本身就是一个有源元件，而不只是入射光束路径上的一个无源几何体。 英文

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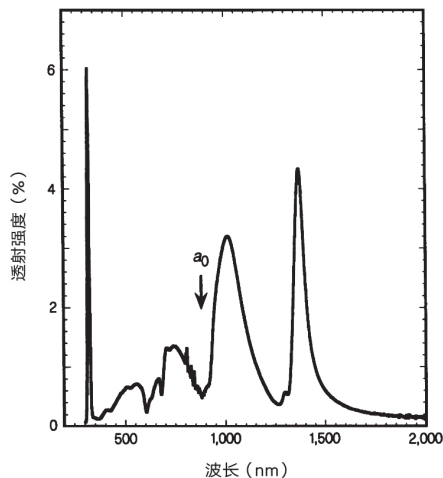


图1 . 一个银阵列 ($a_0 = 0.9 \mu\text{m}$, $d = 150 \text{ nm}$, $t = 200 \text{ nm}$) 的零级透射光谱 [英文](#)

为理解这种现象的来由，我们检测了它对于诸如孔洞直径、周期、金属膜厚度和类型等所有可能变量的依赖性。由于本快报篇幅有限，无法描述所有实验的细节，因此我们总结了观察结果并说明了决定这些光谱的形状的一些关键因素。首先，阵列的周期决定了峰的位置。如图2a所示，最大值的位置严格地与周期成比例，而不依赖于所用金属（银、铬、金）、孔洞直径和薄膜厚度。峰的宽度显然强烈地依赖于圆柱形谐振腔的纵横比 (t/d ，或厚度除以直径)（图2a）。当 $t/d = 0.2$ 时，峰很宽而且刚刚可以分辨出来，而当该比值达到约1时具有最高清晰度。进一步的变窄可能和单个孔洞的性质有关。图2b中显示出光谱对于薄膜厚度的依赖性，其中银膜厚度分别为 $0.2 \mu\text{m}$ 和 $0.5 \mu\text{m}$ 。本底等离子体激元峰的强度在这个范围内快速下降，而较长波长处的峰强度随着厚度变化大致呈线性下降。光谱随着栅格类型——例如阵列究竟是方形还是三角形栅格——发生显著变化。 [英文](#)

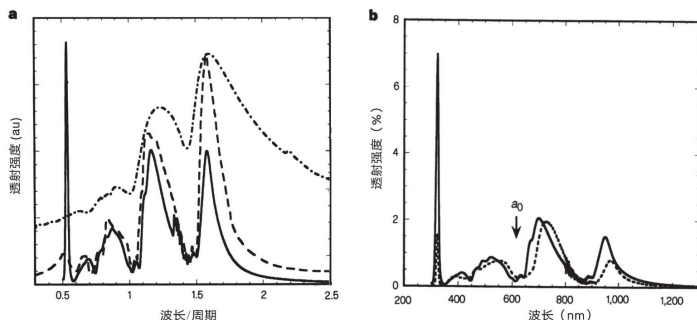


图2 . 参数对于零级透射光谱的影响。a，作为 λ/a_0 的函数的各种方形阵列的光谱。实线：银，

$a_0 = 0.6 \mu\text{m}$, $d = 150 \text{ nm}$, $t = 200 \text{ nm}$; 虚线 : 金 , $a_0 = 1.0 \mu\text{m}$, $d = 350 \text{ nm}$, $t = 300 \text{ nm}$; 点划线 : 铬 , $a_0 = 1.0 \mu\text{m}$, $d = 500 \text{ nm}$, $t = 100 \text{ nm}$ 。 **b** , 只有厚度不同的两个相同银阵列的光谱。实线 : $t = 200 \text{ nm}$; 虚线 : $t = 500 \text{ nm}$ (为便于比较 , 此光谱已乘以倍数1.75) 。对两个阵列同时有 : $a_0 = 0.6 \mu\text{m}$; $d = 150 \text{ nm}$ 。 [英文](#)

将这种现象与表面等离子体激元 (SP) 联系起来的两条重要线索来自下面的观测结果。其一是 , 由锗薄膜加工制成的孔洞阵列中不存在透射增强现象 , 表明了薄膜金属的重要性。另一条线索是在金属样品中光谱的角度依赖性。如图3所示 , 即使角度变化很小时 , 零级透射光谱也会发生明显的变化。图3是角度间隔为 2° 时记录下来的光谱。谱峰强度发生变化 , 并且分裂成向相反方向移动的新谱峰。这正是光与反射光栅中表面等离子体激元耦合时观测到的行为^[9-14]。表面等离子体激元是金属界面上表面电荷的振荡 , 当它们的动量与入射光子以及光栅的动量满足如下表达式时将受到激发 :

$$k_{\text{sp}} = k_x \pm nG_x \pm mG_y$$

其中 k_{sp} 是表面等离子体激元波矢 , $k_x = (2\pi / \lambda) \sin\theta$ 是入射光子波矢在光栅平面内的分量 , 而 $G_x = G_y = 2\pi / a_0$ 是方形阵列的光栅动量波矢。因此 , 如果入射角 θ 变化 , 入射辐射将激发不同的表面等离子体激元模式 ; 通过记录作为 k_x 的函数的峰值能量 , 我们得到了图4中所显示的色散关系。这幅图揭示了二维阵列中表面等离子体激元的带结构 , 而且它清楚地阐明了具有约30 meV到50 meV能量的带隙的存在 ; 它们来源于表面等离子体激元与栅格相互作用导致的简并提升。色散曲线的外推得到在 k 轴上的截距 , 其数值在依据周期 $(2\pi / a_0)$ 预期的实验误差 (约10%) 之内。如同预期 , 图3和图4中的结果也对极化很敏感 , 但是由于金属薄膜中晶粒内在结构间的差异 , 目前还不能做出明确的归属。

[英文](#)

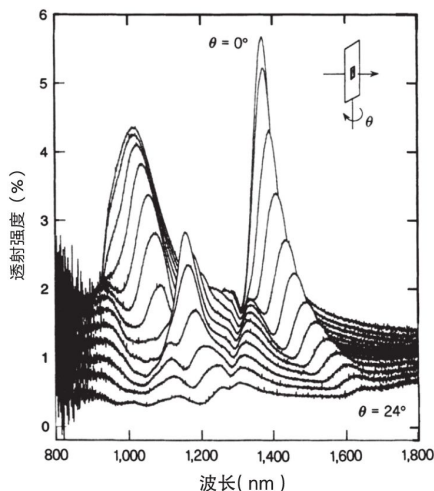


图3．作为光线入射角函数的零级透射光谱。对于一个方形银阵列每隔 2° 测一次谱图，一直测到 24° ($a_0 = 0.9 \mu\text{m}$, $d = 150 \text{ nm}$, $t = 200 \text{ nm}$)。为清晰起见，各个谱之间在垂直方向上错开0.1%。

英文

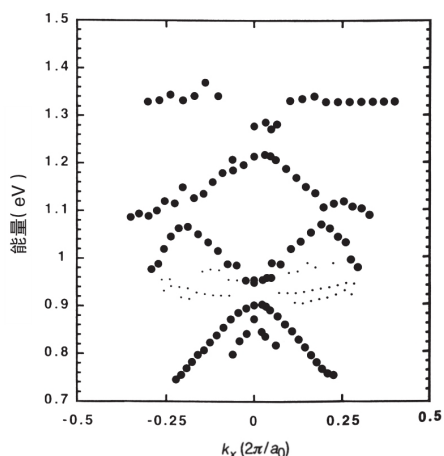


图4．沿阵列[10]方向的色散曲线（实心圆点）。这些曲线是利用图3中透射峰的能量得到的。动量 k_x 位于阵列平面内，由 $k_x = (2\pi / \lambda) \sin \theta$ 给出，其中 θ 是光束的入射角（单位归一化为 $2\pi / a_0$ ）。由较小的点组成的曲线所对应的峰，其幅度要弱很多，由于随动量变化发生的偏移并不明显，因此与带结构的关联不能确定。

英文

在我们的实验中，光与表面等离子体激元的耦合是在透射中而不是在反射中观测到的，这与此前对反射光栅上的表面等离子体激元的研究相反。在那些研究中，光与表面等离子体激元的耦合是作为强度在不同衍射级之间的重新分配观测到的。即使是在洛赫比勒对线光栅的透射研究中^[15]，表面等离子体激元的影响也是通过零级透射光中的凹陷观测到的。关于线栅的红外性质，已经有大量文献表明它有一个以 $\lambda \approx 1.2a_0$

为中心的宽透射；可以用类似于电路的感应效应对此进行解释^[16,17]。我们的结果表明，由于光与亚波长孔洞二维阵列的表面等离子体激元耦合，透射光将明显增强。此外，我们的结果还指出了很多用现有理论无法解释的独特性状。位于金属-空气界面上的表面等离子体激元模式明显不同于位于金属-石英界面上的。但是，无论是从金属一侧还是石英一侧对样品进行光照，所得光谱都是一样的。目前，我们还不知道导致孔洞透射效率大于1的前后表面上等离子体激元之间耦合的详细机制。厚度依赖性（参见图2b）意味着孔洞对于调制这类耦合起着重要的作用，也意味着通过孔洞中的强烈散射，非辐射表面等离子体激元模式将转化为辐射模式。 [英文](#)

在光子带隙阵列中^[2,4]，材料在除去带隙中的能量之外的所有波长处都是无源、半透明的。在当前的阵列中，材料起到有源的作用（通过等离子体激元），并且在除去发生耦合的那些波长之外的所有波长处都是不透明的。这两种现象的结合或整合可能产生无论从基础原理还是技术性角度来讲都极为有趣的光学特性。光能有效地透过比波长小很多的孔洞并突破孔洞间衍射的限制，对这一点的证明可以对诸如新型近场扫描光学显微镜^[6]或者亚波长光刻法的设计等有所启发。对这些结果的理论分析可能会有助于对这种超强透射现象有更深入的理解。也许只有到那时我们才有望掌握这些发现的全部意义。 [英文](#)

（王耀杨 翻译；宋心琦 审稿）

A Silicon-based Nuclear Spin Quantum Computer

B. E. Kane

In the 1980s, physicists began trying to build computing devices that exploit quantum effects, which could be much more powerful than classical devices, at least for certain computational tasks. The practical development of such machines was immensely challenging because of their inherent sensitivity to disruption from the environment. Here Australian physicist Bruce Kane proposes a scheme for implementing a quantum computer by storing its information in the relatively isolated spins of nuclei of dopant atoms inserted into silicon electronic devices. Logical operations, he suggests, could be performed on these spins with external electric fields, and measurements made with currents of spin-polarized electrons. Practical quantum computers are now being developed, and this strategy remains one of many being explored. [中文](#)

Quantum computers promise to exceed the computational efficiency of ordinary classical machines because quantum algorithms allow the execution of certain tasks in fewer steps. But practical implementation of these machines poses a formidable challenge. Here I present a scheme for implementing a quantum-mechanical computer. Information is encoded onto the nuclear spins of donor atoms in doped silicon electronic devices. Logical operations on

individual spins are performed using externally applied electric fields, and spin measurements are made using currents of spin-polarized electrons. The realization of such a computer is dependent on future refinements of conventional silicon electronics. [中文](#)

ALTHOUGH the concept of information underlying all modern computer technology is essentially classical, physicists know that nature obeys the laws of quantum mechanics. The idea of a quantum computer has been developed theoretically over several decades to elucidate fundamental questions concerning the capabilities and limitations of machines in which information is treated quantum mechanically^{1,2}. Specifically, in quantum computers the ones and zeros of classical digital computers are replaced by the quantum state of a two-level system (a qubit). Logical operations carried out on the qubits and their measurement to determine the result of the computation must obey quantum-mechanical laws. Quantum computation can in principle only occur in systems that are almost completely isolated from their environment and which consequently must dissipate no energy during the process of computation, conditions that are extraordinarily difficult to fulfil in practice. [中文](#)

Interest in quantum computation has increased dramatically in the past four years because of two important insights: first, quantum algorithms (most notably for prime factorization^{3,4} and for exhaustive search⁵) have been developed that outperform the best known algorithms doing the same tasks on a classical computer. These algorithms require that the internal state of the quantum computer be controlled with extraordinary precision, so that the coherent quantum state upon which the quantum algorithms rely is not destroyed. Because completely preventing decoherence (uncontrolled interaction of a quantum system with its surrounding environment) is impossible,

the existence of quantum algorithms does not prove that they can ever be implemented in a real machine. 中文

The second critical insight has been the discovery of quantum error-correcting codes that enable quantum computers to operate despite some degree of decoherence and which may make quantum computers experimentally realizable^{6,7}. The tasks that lie ahead to create an actual quantum computer are formidable: Preskill⁸ has estimated that a quantum computer operating on 10^6 qubits with a 10^{-6} probability of error in each operation would exceed the capabilities of contemporary conventional computers on the prime factorization problem. To make use of error-correcting codes, logical operations and measurement must be able to proceed in parallel on qubits throughout the computer. 中文

The states of spin $1/2$ particles are two-level systems that can potentially be used for quantum computation. Nuclear spins have been incorporated into several quantum computer proposals⁹⁻¹² because they are extremely well isolated from their environment and so operations on nuclear spin qubits could have low error rates. The primary challenge in using nuclear spins in quantum computers lies in measuring the spins. The bulk spin resonance approach to quantum computation^{11,12} circumvents the single-spin detection problem essentially by performing quantum calculations in parallel in a large number of molecules and determining the result from macroscopic magnetization measurements. The measurable signal decreases with the number of qubits, however, and scaling this approach above about ten qubits will be technically demanding³⁷. 中文

To attain the goal of a 10^6 qubit quantum computer, it has been suggested that a “solid state” approach¹³ might eventually replicate the enormous success of modern electronics fabrication technology. An attractive alternative approach to nuclear spin quantum computation is to incorporate nuclear spins into an electronic device

and to detect the spins and control their interactions electronically¹⁴. Electron and nuclear spins are coupled by the hyperfine interaction¹⁵. Under appropriate circumstances, polarization is transferred between the two spin systems and nuclear spin polarization is detectable by its effect on the electronic properties of a sample^{16,17}. Electronic devices for both generating and detecting nuclear spin polarization, implemented at low temperatures in GaAs / $\text{Al}_x\text{Ga}_{1-x}\text{As}$ heterostructures, have been developed¹⁸, and similar devices have been incorporated into nanostructures^{19,20}. Although the number of spins probed in the nanostructure experiments is still large ($\sim 10^{11}$; ref. 19), sensitivity will improve in optimized devices and in systems with larger hyperfine interactions. [中文](#)

Here I present a scheme for implementing a quantum computer on an array of nuclear spins located on donors in silicon, the semiconductor used in most conventional computer electronics. Logical operations and measurements can in principle be performed independently and in parallel on each spin in the array. I describe specific electronic devices for the manipulation and measurement of nuclear spins, fabrication of which will require significant advances in the rapidly moving field of nanotechnology. Although it is likely that scaling the devices proposed here into a computer of the size envisaged by Preskill⁸ will be an extraordinary challenge, a silicon-based quantum computer is in a unique position to benefit from the resources and ingenuity being directed towards making conventional electronics of ever smaller size and greater complexity. [中文](#)

Quantum Computation with a ^{31}P Array in Silicon

The strength of the hyperfine interaction is proportional to the probability density of the electron wavefunction at the nucleus. In semiconductors, the electron wavefunction extends over large distances through the crystal lattice. Two nuclear spins can consequently interact with the same electron, leading to electron-

mediated or indirect nuclear spin coupling¹⁵. Because the electron is sensitive to externally applied electric fields, the hyperfine interaction and electron-mediated nuclear spin interaction can be controlled by voltages applied to metallic gates in a semiconductor device, enabling the external manipulation of nuclear spin dynamics that is necessary for quantum computation. [中文](#)

The conditions required for electron-coupled nuclear spin computation and single nuclear spin detection can arise if the nuclear spin is located on a positively charged donor in a semiconductor host. The electron wavefunction is then concentrated at the donor nucleus (for s orbitals and energy bands composed primarily of them), yielding a large hyperfine interaction energy. For shallow-level donors, however, the electron wavefunction extends tens or hundreds of ångströms away from the donor nucleus, allowing electron-mediated nuclear spin coupling to occur over comparable distances. The quantum computer proposed here comprises an array of such donors positioned beneath the surface of a semiconductor host (Fig. 1). A quantum mechanical calculation proceeds by the precise control of three external parameters: (1) gates above the donors control the strength of the hyperfine interactions and hence the resonance frequency of the nuclear spins beneath them; (2) gates between the donors turn on and off electron-mediated coupling between the nuclear spins¹³; (3) a globally applied a.c. magnetic field B_{ac} flips nuclear spins at resonance. Custom adjustment of the coupling of each spin to its neighbours and to B_{ac} enables different operations to be performed on each of the spins simultaneously. Finally, measurements are performed by transferring nuclear spin polarization to the electrons and determining the electron spin state by its effect on the orbital wavefunction of the electrons, which can be probed using capacitance measurements between adjacent gates. [中文](#)

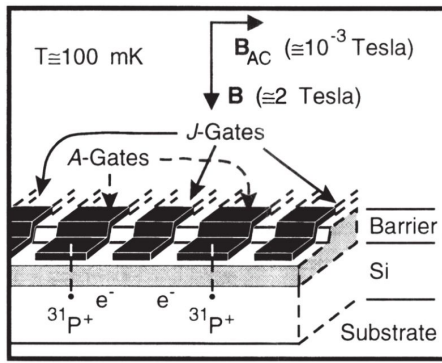


Fig. 1. Illustration of two cells in a one-dimensional array containing ^{31}P donors and electrons in a Si host, separated by a barrier from metal gates on the surface. “A gates” control the resonance frequency of the nuclear spin qubits; “J gates” control the electron-mediated coupling between adjacent nuclear spins. The ledge over which the gates cross localizes the gate electric field in the vicinity of the donors. [中文](#)

An important requirement for a quantum computer is to isolate the qubits from any degrees of freedom that may lead to decoherence. If the qubits are spins on a donor in a semiconductor, nuclear spins in the host are a large reservoir with which the donor spins can interact. Consequently, the host should contain only nuclei with spin $I=0$. This simple requirement unfortunately eliminates all III–V semiconductors as host candidates, because none of their constituent elements possesses stable $I=0$ isotopes²¹. Group IV semiconductors are composed primarily $I=0$ isotopes and can in principle be purified to contain only $I=0$ isotopes. Because of the advanced state of Si materials technology and the tremendous effort currently underway in Si nanofabrication, Si is the obvious choice for the semiconductor host. [中文](#)

The only $I=1/2$ shallow (group V) donor in Si is ^{31}P . The Si: ^{31}P system was exhaustively studied 40 years ago in the first electron–nuclear double-resonance experiments^{22,23}. At sufficiently low ^{31}P concentrations at temperature $T=1.5 \text{ K}$, the electron spin relaxation time is thousands of seconds and the ^{31}P nuclear spin relaxation time exceeds 10 hours. It is likely that at millikelvin temperatures the phonon limited ^{31}P relaxation time is of the order of 10^{18} seconds (ref.

24), making this system ideal for quantum computation.

[中文](#)

The purpose of the electrons in the computer is to mediate nuclear spin interactions and to facilitate measurement of the nuclear spins. Irreversible interactions between electron and nuclear spins must not occur as the computation proceeds: the electrons must be in a non-degenerate ground state throughout the computation. At sufficiently low temperatures, electrons only occupy the lowest energy-bound state at the donor, whose twofold spin degeneracy is broken by an applied magnetic field B . (The valley degeneracy of the Si conduction band is broken in the vicinity of the donor²⁵. The lowest donor excited state is approximately 15 meV above the ground state²³.) The electrons will only occupy the lowest energy spin level when $2\mu_B B \gg kT$, where μ_B is the Bohr magneton. (In Si, the Landé g -factor is very close to $+2$, so $g=2$ is used throughout this discussion.) The electrons will be completely spin-polarized ($n_\uparrow/n_\downarrow < 10^{-6}$) when $T \leq 100$ mK and $B \geq 2$ tesla. A quantum-mechanical computer is non-dissipative and can consequently operate at low temperatures. Dissipation will arise external to the computer from gate biasing and from eddy currents caused by B_{ac} , and during polarization and measurement of the nuclear spins. These effects will determine the minimum operable temperature of the computer. For this discussion, I will assume $T=100$ mK and $B=2$ T. Note that these conditions do not fully polarize the nuclear spins, which are instead aligned by interactions with the polarized electrons.

[中文](#)

Magnitude of Spin Interactions in Si:³¹P

The size of the interactions between spins determines both the time required to do elementary operations on the qubits and the separation necessary between donors in the array. The hamiltonian for a nuclear spin-electron system in Si, applicable for an $I=1/2$ donor nucleus and

with B_z is
$$H_{\text{en}} = \mu_B B \sigma_z^e - g_n \mu_n B \sigma_z^n + A \sigma_z^e \cdot \sigma_z^n$$
, where σ are the Pauli

spin matrices (with eigenvalues ± 1), μ_n is the nuclear magneton, g_n is the nuclear g -factor (1.13 for ^{31}P ; ref. 21), and $A = \frac{8}{3} \pi \mu_B g_n \mu_n |\Psi(0)|^2$ is the contact hyperfine interaction energy, with $|\Psi(0)|^2$, the probability density of the electron wavefunction, evaluated at the nucleus. If the electron is in its ground state, the frequency separation of the nuclear levels is, to second order

$$h\nu_A = 2g_n\mu_n B + 2A + \frac{2A^2}{\mu_B B} \quad (1)$$

In Si: ^{31}P , $2A / h = 58$ MHz, and the second term in equation (1) exceeds the first term for $B < 3.5$ T. 中文

An electric field applied to the electron–donor system shifts the electron wavefunction envelope away from the nucleus and reduces the hyperfine interaction. The size of this shift, following estimates of Kohn²⁵ of shallow donor Stark shifts in Si, is shown in Fig. 2 for a donor 200 Å beneath a gate. A donor nuclear spin–electron system close to an “A gate” functions as a voltage-controlled oscillator: the precession frequency of the nuclear spin is controllable externally, and spins can be selectively brought into resonance with B_{ac} , allowing arbitrary rotations to be performed on each nuclear spin. 中文

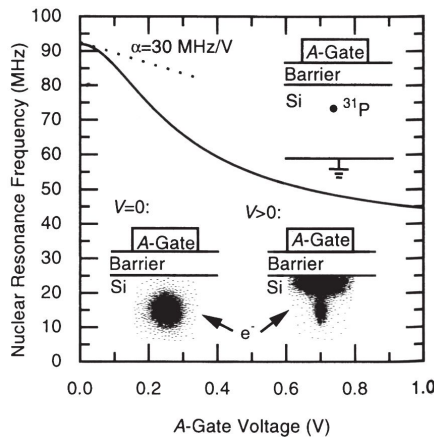


Fig. 2. An electric field applied to an A gate pulls the electron wavefunction away from the donor and towards the barrier, reducing the hyperfine interaction and the resonance frequency of the nucleus. The donor nucleus–electron system is a voltage-controlled oscillator

Quantum mechanical computation requires, in addition to single spin rotations, the two-qubit “controlled rotation” operation, which rotates the spin of a target qubit through a prescribed angle if, and only if, the control qubit is oriented in a specified direction, and leaves the orientation of the control qubit unchanged^{26,27}. Performing the controlled rotation operation requires nuclear-spin exchange between two donor nucleus – electron spin systems¹³, which will arise from electron-mediated interactions when the donors are sufficiently close to each other. The hamiltonian of two coupled donor nucleus–electron systems, valid at energy scales small compared to the donor – electron binding energy, is $H = H(B) + A_1 \sigma^{1n} \cdot \sigma^{2e} + A_2 \sigma^{2n} \cdot \sigma^{2e} + J \sigma^{1e} \cdot \sigma^{2e}$, where $H(B)$ are the magnetic field interaction terms for the spins. A_1 and A_2 are the hyperfine interaction energies of the respective nucleus–electron systems. $4J$, the exchange energy, depends on the overlap of the electron wavefunctions. For well separated donors²⁸

$$4J(r) \cong 1.6 \frac{e^2}{\epsilon a_B} \left(\frac{r}{a_B} \right)^{\frac{5}{2}} \exp \left(\frac{-2r}{a_B} \right) \quad (2)$$

where r is the distance between donors, ϵ is the dielectric constant of the semiconductor, and a_B is the semiconductor Bohr radius. This function, with values appropriate for Si, is plotted in Fig. 3. Equation (2), originally derived for H atoms, is complicated in Si by its valley degenerate anisotropic band structure²⁹. Exchange coupling terms from each valley interfere, leading to oscillatory behaviour of $J(r)$. In this discussion, the complications introduced by Si band structure will be neglected. In determining $J(r)$ in Fig. 3, the transverse mass for Si ($\cong 0.2m_e$) has been used, and $a_B = 30 \text{ \AA}$. Because J is proportional to the electron wave function overlap, it can be varied by an electrostatic potential imposed by a “J-gate” positioned between the donors¹³. As shall be seen below, significant coupling between nuclei will occur when $4J \approx \mu_B B$, and this condition approximates the necessary separation between donors of 100–200 $\text{\AA}$. Whereas actual separations

may be considerably larger than this value because the J gate can be biased positively to reduce the barrier between donors, the gate sizes required for the quantum computer are near the limit of current electronics fabrication technology. 中文

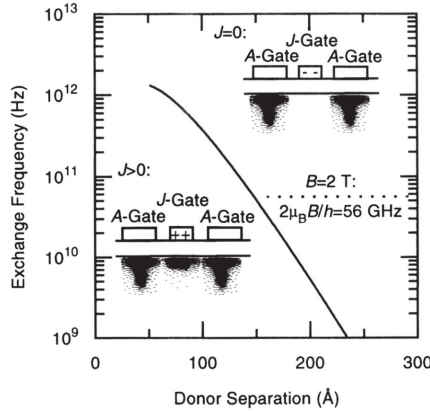


Fig. 3. J gates vary the electrostatic potential barrier V between donors to enhance or reduce exchange coupling, proportional to the electron wavefunction overlap. The exchange frequency ($4J / h$) when $V=0$ is plotted for Si. 中文

For two-electron systems, the exchange interaction lowers the electron singlet ($|\uparrow\downarrow - \downarrow\uparrow\rangle$) energy with respect to the triplets³⁰. (The $|\uparrow\downarrow\rangle$ notation is used here to represent the electron spin state, and the $|01\rangle$ notation the nuclear state; in the $|\downarrow\downarrow 11\rangle$ state, all spins point in the same direction. For simplicity, normalization constants are omitted.)

In a magnetic field, however, $|\downarrow\downarrow\rangle$ will be the ground state if $J < \mu_B B / 2$ (Fig. 4a). In the $|\downarrow\downarrow\rangle$ state, the energies of the nuclear states can be calculated to second order in A using perturbation theory. When

$A_1 = A_2 = A$, the $|10-01\rangle$ state is lowered in energy with respect to $|10+01\rangle$ by:

$$h\nu_J = 2A^2 \left(\frac{1}{\mu_B B - 2J} - \frac{1}{\mu_B B} \right) \quad (3)$$

The $|11\rangle$ state is above the $|10+01\rangle$ state and the $|00\rangle$ state below the $|10-01\rangle$ state by an energy $h\nu_A$, given in equation (1). For the Si:³¹P system at $B=2$ T and for $4J / h = 30$ GHz, equation (3) yields

$\nu_J=75$ kHz. This nuclear spin exchange frequency approximates the rate at which binary operations can be performed on the computer (ν_J can be increased by increasing J , but at the expense of also increasing the relaxation rate of the coupled nuclear–electron spin excitations). The speed of single spin operations is determined by the size of B_{ac} and is comparable to 75 kHz when $B_{ac}=10^{-3}$ T. 中文

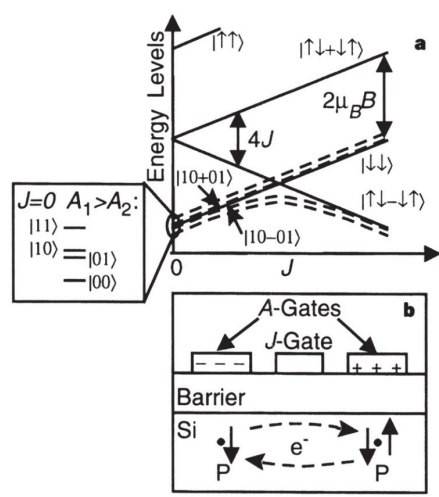


Fig. 4. Two qubit quantum logic and spin measurement. **a**, Electron (solid lines) and lowest energy-coupled electron – nuclear (dashed lines) energy levels as a function of J . When $J<\mu_B B / 2$, two qubit computations are performed by controlling the $|10-01\rangle-|10+01\rangle$ level splitting with a J gate. Above $J=\mu_B B / 2$, the states of the coupled system evolve into states of differing electron polarization. The state of the nucleus at $J=0$ with the larger energy splitting (controllable by the A gate bias) determines the final electron spin state after an adiabatic increase in J . **b**, Only $|\uparrow\downarrow-\downarrow\uparrow\rangle$ electrons can make transitions into states in which electrons are bound to the same donor (D^- states). Electron current during these transitions is measurable using capacitive techniques, enabling the underlying spin states of the electrons and nuclei to be determined. 中文

Spin Measurements

Measurement of nuclear spins in the proposed quantum computer is accomplished in a two-step process: distinct nuclear spin states are adiabatically converted into states with different electron polarization, and the electron spin is determined by its effect on the symmetry of the orbital wavefunction of an exchange-coupled two-electron system. A procedure for accomplishing this conversion is shown in Fig. 4.

While computation is done when $J < \mu_B B / 2$ and the electrons are fully polarized, measurements are made when $J > \mu_B B / 2$, and $|\uparrow\downarrow - \downarrow\uparrow\rangle$ states have the lowest energy (Fig. 4a). As the electron levels cross, the $|\downarrow\downarrow\rangle$ and $|\uparrow\downarrow - \downarrow\uparrow\rangle$ states are coupled by hyperfine interactions with the nuclei. During an adiabatic increase in J , the two lower-energy nuclear spin states at $J=0$ evolve into $|\uparrow\downarrow - \downarrow\uparrow\rangle$ states when $J > \mu_B B / 2$, whereas the two higher-energy nuclear states remain $|\downarrow\downarrow\rangle$. If, at $J=0$, $A_1 > A_2$, the orientation of nuclear spin 1 alone will determine whether the system evolves into the $|\uparrow\downarrow - \downarrow\uparrow\rangle$ or the $|\downarrow\downarrow\rangle$ state during an adiabatic increase in J . 中文

A method to detect the electron spin state by using electronic means is shown in Fig. 4b. Both electrons can become bound to the same donor (a D^- state) if the A gates above the donors are biased appropriately. In Si:P, the D^- state is always a singlet with a second electron binding energy of 1.7 meV (refs 31, 32). Consequently, a differential voltage applied to the A gates can result in charge motion between the donors that only occurs if the electrons are in a singlet state. This charge motion is measurable using sensitive single-electron capacitance techniques³³. This approach to spin measurement produces a signal that persists until the electron spin relaxes, a time that, as noted above, can be thousands of seconds in Si:P. 中文

The spin measurement process can also be used to prepare nuclear spins in a prescribed state by first determining the state of a spin and flipping it if necessary so that it ends up in the desired spin state. As with the spin computation procedures already discussed, spin measurement and preparation can in principle be performed in parallel throughout the computer. 中文

Initializing the Computer

Before any computation, the computer must be initialized by calibrating the A gates and the J gates. Fluctuations from cell to cell in

the gate biases necessary to perform logical operations are an inevitable consequence of variations in the positions of the donors and in the sizes of the gates. The parameters of each cell, however, can be determined individually using the measurement capabilities of the computer, because the measurement technique discussed here does not require precise knowledge of the J and A couplings. The A -gate voltage at which the underlying nuclear spin is resonant with an applied B_{ac} can be determined using the technique of adiabatic fast passage³⁴: when $B_{ac} = 0$, the nuclear spin is measured and the A gate is biased at a voltage known to be off resonance. B_{ac} is then switched on, and the A gate bias is swept through a prescribed voltage interval. B_{ac} is then switched off and the nuclear spin is measured again. The spin will have flipped if, and only if, resonance occurred within the prescribed A -gate voltage range. Testing for spin flips in increasingly small voltage ranges leads to the determination of the resonance voltage. Once adjacent A gates have been calibrated, the J gates can be calibrated in a similar manner by sweeping J -gate biases across resonances of two coupled cells. [中文](#)

This calibration procedure can be performed in parallel on many cells, so calibration is not a fundamental impediment to scaling the computer to large sizes. Calibration voltages can be stored on capacitors located on the Si chip adjacent to the quantum computer. External controlling circuitry would thus need to control only the timing of gate biases, and not their magnitudes. [中文](#)

Spin Decoherence Introduced by Gates

In the quantum computer architecture outlined above, biasing of A gates and J gates enables custom control of the qubits and their mutual interactions. The presence of the gates, however, will lead to decoherence of the spins if the gate biases fluctuate away from their desired values. These effects need to be considered to evaluate the performance of any gate-controlled quantum computer. During the

computation, the largest source of decoherence is likely to arise from voltage fluctuations on the A gates. (When $J < \mu_B B / 2$, modulation of the state energies by the J gates is much smaller than by the A gates. J exceeds $\mu_B B / 2$ only during the measurement process, when decoherence will inevitably occur.) The precession frequencies of two spins in phase at $t=0$ depends on the potentials on their respective A gates. Differential fluctuations of the potentials produce differences in the precession frequency. At some later time $t=t_\phi$, the spins will be 180° out of phase; t_ϕ can be estimated by determining the transition rate between $|10+01\rangle$ (spins in phase) and $|10-01\rangle$ (spins 180° out of phase) of a two-spin system. The hamiltonian that couples these states is $H_\phi = \frac{1}{4} \hbar \Delta (\sigma_z^{1n} - \sigma_z^{2n})$, where Δ is the fluctuating differential precession frequency of the spins. Standard treatment of fluctuating hamiltonians³⁴ predicts: $t_\phi^{-1} = \pi^2 S_\Delta(\nu_{st})$, where S_Δ is the spectral density of the frequency fluctuations, and ν_{st} is the frequency difference between the $|10-01\rangle$ and $|10+01\rangle$ states. At a particular bias voltage, the A gates have a frequency tuning parameter $\alpha = d\Delta / dV$. Thus:

$$t_\phi^{-1} = \pi^2 \alpha^2 \langle V \rangle S_V(\nu_{st}) \tag{4}$$

where S_V is the spectral density of the gate voltage fluctuations. 中文

S_V for good room temperature electronics is of order $10^{-18} \text{ V}^2 / \text{Hz}$, comparable to the room temperature Johnson noise of a $50\text{-}\Omega$ resistor. The value of α , estimated from Fig. 2, is $10\text{--}100 \text{ MHz V}^{-1}$, yielding $t_\phi = 10\text{--}1,000 \text{ s}$; α is determined by the size of the donor array cells and cannot readily be reduced (to increase t_ϕ) without reducing the exchange interaction between cells. Because α is a function of the gate bias (Fig. 2), t_ϕ can be increased by minimizing the voltage applied to the A gates. 中文

Although equation (4) is valid for white noise, at low frequencies it is

likely that materials-dependent fluctuations ($1 / f$ noise) will be the dominant cause of spin dephasing. Consequently, it is difficult to give hard estimates of t_ϕ for the computer. Charge fluctuations within the computer (arising from fluctuating occupancies of traps and surface states, for example) are likely to be particularly important, and minimizing them will place great demands on computer fabrication.

[中文](#)

Although materials-dependent fluctuations are difficult to estimate, the low-temperature operations of the computer and the dissipationless nature of quantum computing mean that, in principle, fluctuations can be kept extremely small: using low-temperature electronics to bias the gates (for instance, by using on chip capacitors as discussed above) could produce $t_\phi \approx 10^6$ s. Electronically controlled nuclear spin quantum computers thus have the theoretical capability to perform at least 10^5 to perhaps 10^{10} logical operations during t_ϕ , and can probably meet Preskill's criterion⁸ for an error probability of 10^{-6} per qubit operation.

[中文](#)

Constructing the Computer

Building the computer presented here will obviously be an extraordinary challenge: the materials must be almost completely free of spin ($I \neq 0$ isotopes) and charge impurities to prevent dephasing fluctuations from arising within the computer. Donors must be introduced into the material in an ordered array hundreds of Å beneath the surface. Finally, gates with lateral dimensions and separations ~ 100 Å must be patterned on the surface, registered to the donors beneath them. Although it is possible that the computer can use SiO_2 as the barrier material (the standard MOS technology used in most current conventional electronics), the need to reduce disorder and fluctuations to a minimum means that heteroepitaxial materials, such as Si / SiGe, may ultimately be preferable to Si / SiO_2 .

[中文](#)

The most obvious obstacle to building to the quantum computer presented above is the incorporation of the donor array into the Si layer beneath the barrier layer. Currently, semiconductor structures are deposited layer by layer. The δ -doping technique produces donors lying on a plane in the material, with the donors randomly distributed within the plane. The quantum computer envisaged here requires that the donors be placed into an ordered one- or two-dimensional array; furthermore, precisely one donor must be placed into each array cell, making it extremely difficult to create the array by using lithography and ion implantation or by focused deposition. Methods currently under development to place single atoms on surfaces using ultra-high-vacuum scanning tunnelling microscopy³⁵ or atom optics techniques³⁶ are likely candidates to be used to position the donor array. A challenge will be to grow high-quality Si layers on the surface subsequent to placement of the donors. [中文](#)

Fabricating large arrays of donors may prove to be difficult, but two-spin devices, which can be used to test the logical operations and measurement techniques presented here, can be made using random doping techniques. Although only a small fraction of such devices will work properly, adjacent conventional Si electronic multiplexing circuitry can be used to examine many devices separately. The relative ease of fabricating such “hybrid”(quantum–conventional) circuits is a particularly attractive feature of Si-based quantum computation.

[中文](#)

In a Si-based nuclear spin quantum computer, the highly coherent quantum states necessary for quantum computation are incorporated into a material in which the ability to implement complex computer architectures is well established. The substantial challenges facing the realization of the computer, particularly in fabricating 100-Å-scale gated devices, are similar to those facing the next generation of conventional electronics; consequently, new manufacturing

technologies being developed for conventional electronics will bear directly on efforts to develop a quantum computer in Si. Quantum computers sufficiently complex that they can achieve their theoretical potential may thus one day be built using the same technology that is used to produce conventional computers. 中文

(393, 133-137; 1998)

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Received 10 November 1997; accepted 24 February 1998.

References:

1. Steane, A. Quantum computing. *Rep. Prog. Phys.* **61**, 117-173 (1998).
2. Bennett, C. H. Quantum information and computation. *Physics Today* 24-30 (Oct. 1995).
3. Shor, P. W. in *Proc. 35th Annu. Symp. Foundations of Computer Science* (ed. Goldwasser, S.) 124-134 (IEEE Computer Society, Los Alamitos, CA, 1994).
4. Ekert, A. & Jozsa, R. Quantum computation and Shor's factoring algorithm. *Rev. Mod. Phys.* **68**, 733-753 (1996).
5. Grover, L. K. Quantum mechanics helps in searching for a needle in a haystack. *Phys. Rev. Lett.* **79**, 325-328 (1997).
6. Calderbank, A. R. & Shor, P. W. Good quantum error correcting codes exist. *Phys. Rev. A* **54**, 1098-1105 (1996).
7. Steane, A. M. Error correcting codes in quantum theory. *Phys. Rev. Lett.* **77**, 793-797 (1996).
8. Preskill, J. Reliable quantum computers. *Proc. R. Soc. Lond. A* **454**, 385-410 (1998).
9. Lloyd, S. A potentially realizable quantum computer. *Science* **261**, 1569-1571 (1993).
10. DiVincenzo, D. P. Quantum computation. *Science* **270**, 255-261 (1995).
11. Gershenfeld, N. A. & Chuang, I. L. Bulk spin-resonance quantum computation. *Science* **275**, 350-356 (1997).
12. Cory, D. G., Fahmy, A. F. & Havel, T. F. Ensemble quantum computing by NMR spectroscopy. *Proc. Natl Acad. Sci. USA* **94**, 1634-1639 (1997).
13. Loss, D. & DiVincenzo, D. P. Quantum computation with quantum dots. *Phys. Rev. A* **57**, 120-126 (1998).
14. Privman, V., Vagner, I. D. & Kventsel, G. Quantum computation in quantum Hall systems. *Phys. Lett. A* **239**, 141-146 (1998).
15. Slichter, C. P. *Principles of Magnetic Resonance* 3rd edn, Ch 4 (Springer, Berlin, 1990).
16. Dobers, M., Klitzing, K. v., Schneider, J., Weimann, G. & Ploog, K. Electrical detection of nuclear magnetic resonance in GaAs-Al_xGa_{1-x}As heterostructures. *Phys. Rev. Lett.* **61**, 1650-1653 (1988).

17. Stich, B., Greulich-Weber, S. & Spaeth, J.-M. Electrical detection of electron nuclear double resonance in silicon. *Appl. Phys. Lett.* **68**, 1102-1104 (1996).
18. Kane, B. E., Pfeiffer, L. N. & West, K. W. Evidence for an electric-field-induced phase transition in a spin-polarized two-dimensional electron gas. *Phys. Rev. B* **46**, 7264-7267 (1992).
19. Wald, K. W., Kouwenhoven, L. P., McEuen, P. L., van der Vaart, N. C. & Foxon, C. T. Local dynamic nuclear polarization using quantum point contacts. *Phys. Rev. Lett.* **73**, 1011-1014 (1994).
20. Dixon, D. C., Wald, K. R., McEuen, P. L. & Melloch, M. R. Dynamic polarization at the edge of a two-dimensional electron gas. *Phys. Rev. B* **56**, 4743-4750 (1997).
21. *CRC Handbook of Chemistry and Physics* 77th edn 11-38 (CRC Press, Boca Raton, Florida, 1996).
22. Feher, G. Electron spin resonance on donors in silicon. I. Electronic structure of donors by the electron nuclear double resonance technique. *Phys. Rev.* **114**, 1219-1244 (1959).
23. Wilson, D. K. & Feher, G. Electron spin resonance experiments on donors in silicon. III. Investigation of excited states by the application of uniaxial stress and their importance in relaxation processes. *Phys. Rev.* **124**, 1068-1083 (1961).
24. Waugh, J. S. & Slichter, C. P. Mechanism of nuclear spin-lattice relaxation in insulators at very low temperatures. *Phys. Rev. B* **37**, 4337-4339 (1988).
25. Kohn, W. *Solid State Physics* Vol. 5 (eds Seitz, F. & Turnbull, D.) 257-320 (Academic, New York, 1957).
26. DiVincenzo, D. P. Two-bit gates are universal for quantum computation. *Phys. Rev. A* **51**, 1015-1021 (1995).
27. Lloyd, S. Almost any quantum logic gate is universal. *Phys. Rev. Lett.* **75**, 346-349 (1995).
28. Herring, C. & Flicker, M. Asymptotic exchange coupling of two hydrogen atoms. *Phys. Rev.* **134**, A362-A366 (1964).
29. Andres, K., Bhatt, R. N., Goalwin, P., Rice, T. M. & Walstedt, R. E. Low-temperature magnetic susceptibility of Si:P in the nonmetallic region. *Phys. Rev. B* **24**, 244-260 (1981).
30. Ashcroft, N. W. & Mermin, N. D. in *Solid State Physics* Ch. 32 (Saunders College, Philadelphia, 1976).
31. Larsen, D. M. Stress dependence of the binding energy of D^- centers in Si. *Phys. Rev. B* **23**, 5521-5526 (1981).
32. Larsen, D. M. & McCann, S. Y. Variational studies of two- and three-dimensional D^- centers in magnetic fields. *Phys. Rev. B* **46**, 3966-3970 (1992).
33. Ashoori, R. C. Electrons in artificial atoms. *Nature* **379**, 413-419 (1996).
34. Abragam, A. *Principles of Nuclear Magnetism* (Oxford Univ. Press, London, 1961).
35. Lyding, J. W. UHV STM nanofabrication: progress, technology spin-offs, and challenges. *Proc. IEEE* **85**, 589-600 (1997).
36. Adams, C. S., Sigel, J. & Mlynek, J. Atom optics. *Phys. Rep.* **240**, 143-210 (1994).
37. Warren, W. S. The usefulness of NMR quantum computing. *Science* **277**, 1688-1690 (1997).

Acknowledgements. This work has been supported by the Australian Research Council. I

thank R. G. Clark for encouragement and E. Hellman for suggesting that the work in ref. 18 could be relevant to quantum computation.

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硅基核自旋量子计算机

凯恩

20世纪80年代，物理学家开始尝试构建利用量子效应的计算设备，至少对于某些计算任务而言，它可能比传统设备性能强大得多。由于其对来自环境的干扰具有内在的敏感性，这类机器的实际研发极具挑战性。本文中，澳大利亚物理学家布鲁斯·凯恩提出了一种实现量子计算机的方案，将其信息存储在硅电子器件中内嵌掺杂原子的相对孤立的核自旋中。他建议，逻辑运算可以在外部电场辅助下用这些自旋进行，并用自旋极化电子的电流进行测量。可行的量子计算机正在开发中，该方案仍然是许多正在被探索的策略之一。

[英文](#)

量子计算机的计算效率可能会超过传统经典计算机，因为量子算法允许用更少的步骤来执行某些任务。但是这些机器的实际研发仍然是一个艰巨的挑战。这里我将提出一种构建基于量子力学的计算机的方法。计算信息被编码在掺杂硅的电子器件中施主原子的核自旋上。单个自旋的逻辑运算用外部施加电场来实现，而自旋测量基于自旋极化电子的电流。这样一个计算机的实现依赖于传统硅器件未来的精密程度。

[英文](#)

尽管所有现代计算机所依赖的信息概念本质上都是基于经典理论的，然而物理学家知道自然界遵从量子力学定律。量子计算机的概念在理论上已经发展了几十年，旨在阐明使用量子力学来处理信息的计算机的能力和极限等基本问题^[1,2]。具体而言，在量子计算机中，经典计算机中的0和1被一个二能级系统的量子态（量子比特）所取代。在量子比特上进行的逻辑运算及用来决定计算结果的测量必须遵守量子力学定

律。量子计算理论上只能发生在与外界环境几乎完全隔离的系统中，这样在计算过程中不会存在能量的耗散，这样的苛刻条件在现实中很难满足。 英文

在过去四年中，两个重大的突破使人们对量子计算的兴趣与日俱增。第一个是量子算法（尤其值得一提的是质因子分解^[3,4]和穷举搜索^[5]）的开发，而且这些算法在执行相同任务时优于经典计算机上最著名的算法。这些算法要求量子计算机的内部状态被准确无误地控制，这样量子算法所依赖的相干量子态就不会被破坏。因为完全阻止量子退相干（量子系统和外界环境之间非受控的相互作用）是不可能的，所以量子算法的存在并不能保证它们可以在真实的计算机上面得以实现。 英文

第二个重大的突破是量子纠错码的发现，它可以使量子计算机运行时容忍一定程度的量子退相干，这使得量子计算机在实验上的实现成为可能^[6,7]。眼下制造一台真正的量子计算机的任务是艰巨的：据普雷斯基尔^[8]估计，一台使用 10^6 个量子比特且每次运算误码率为 10^{-6} 的量子计算机可以在质因子分解问题上超过同时代的传统计算机。为了利用纠错码，逻辑运算和测量必须能够在整个计算机的量子比特上并行进行。

英文

自旋为 $1/2$ 的粒子的状态是二能级系统，具备应用于量子计算的潜质。核自旋已经被纳入数个量子计算机提案^[9-12]中，因为它们与外界环境间被很好地隔离，因此利用核自旋比特来运算，误码率可能很低。在量子计算机中使用核自旋的主要挑战在于测量自旋。量子计算的系综自旋共振方法^[11,12]基本上是通过在大量分子上的并行量子计算并由宏观磁化测量确定结果来绕开单个自旋的测量问题。然而可测量信号随着量子比特数目的增多而减少，因此将这种方法扩展到10个量子比特以上将会对技术要求极为苛刻^[37]。 英文

为了实现 10^6 量子比特计算机，有人建议使用“固态”方法^[13]，这种方法也许可以最终复制现代电子器件微加工技术的巨大成功。核自旋量子计算的一种有吸引力的替代方法是将核自旋融合到电子器件中，并且通过电学方式来测量自旋以及控制其之间的相互作用^[14]。电子和核自

旋被超精细相互作用耦合在一起^[15]。在适当情况下，极化可以在两个自旋系统中转移，核自旋极化可以通过其对样品的电子性质的影响来测量^[16,17]。用来产生和探测核自旋极化的电子器件也已经在低温砷化镓（GaAs）/铝镓砷（ $\text{Al}_x\text{Ga}_{1-x}\text{As}$ ）异质结构中实现^[18]，类似的器件也已经被整合到纳米结构中^[19,20]。尽管在纳米结构试验中研究的自旋数目仍然很大（约为 10^{11} ；文献19），但在经过优化的器件中以及更强的超精细相互作用系统中，灵敏度会得到进一步的改善。 [英文](#)

这里我将介绍一种利用位于硅材料施主上面的核自旋阵列来实现量子计算机的方法，硅材料是大多数传统计算机电子学中使用的半导体。理论上逻辑运算和测量可以在阵列中的各个自旋上独立且并行执行。我将介绍特定的电子器件来实现核自旋的控制和测量，其制造需要迅猛发展的纳米科技领域的重大突破。把这里提出的器件缩放到普雷斯基尔^[8]设想的尺寸的计算机中，这也许是一个巨大的挑战，然而，由于人们为了将传统电子器件做得更小且更加复杂的过程中积累了资源和聪明才智，硅基量子计算机仍然具有独特的地位。 [英文](#)

使用硅中 ^{31}P 阵列的量子计算

超精细相互作用的强度正比于原子核处电子波函数的概率密度。在半导体中，电子波函数在晶格上延展很长的距离。两个核自旋因此可以和同一个电子相互作用，这就导致了电子介导的或者间接的核自旋耦合^[15]。由于电子对于外加电场的敏感，超精细相互作用以及电子介导的核自旋相互作用可以通过调节施加在半导体器件中金属栅极上的电压来控制，这使量子计算所要求的核自旋动力学的外部调制成为可能。

[英文](#)

如果核自旋位于半导体宿主中带正电的施主上面，电子耦合核自旋计算以及单核自旋检测所需要的条件会被满足。电子波函数将会集中于施主的原子核（对于s轨道和主要由它们组成的能带），产生大的超精细相互作用能。然而对于浅能级施主来说，电子波函数从原子核向外扩展了几十甚至几百埃，从而允许电子介导核自旋耦合在相对远的距离发生。本文提出的量子计算机包括在半导体宿主表面下方的一系列这样的施主（如图1）。量子力学计算通过精确控制三个外部参数来进行：

(1) 施主上方的栅极控制超精细相互作用的强度，因此也就控制了栅极下方的核自旋的共振频率；(2) 施主之间的栅极可以用来开通和关闭核自旋之间的电子介导耦合^[13]；(3) 一个对全体施加的交变磁场 B_{ac} 用来翻转与磁场共振的核自旋。单独调节每个自旋之间的耦合以及自旋与外加磁场 B_{ac} 的耦合，使每个自旋上的不同运算可以同时进行。最后，通过转移核自旋极化到电子身上进而影响电子轨道波函数，最终通过测试其对相邻的栅极之间的电容的改变来测得自旋态。 [英文](#)

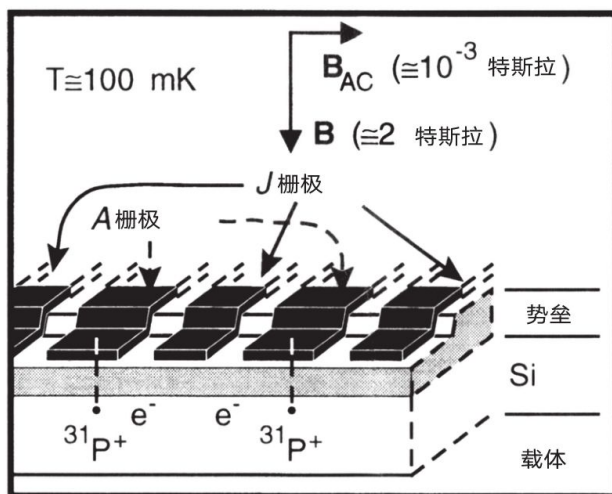


图1. 硅宿主中 ^{31}P 施主和电子的一维阵列中的两个单元的示意图，图中的势垒层将该阵列与表面的金属栅极隔离开。“A栅极”用来控制核自旋量子比特的共振频率。“J栅极”用来控制相邻核自旋的电子介导耦合。栅极末端的台阶状设计使得加在施主附近的电场局域化。 [英文](#)

对于量子计算机来说，一个重要的要求是量子比特应该与可能导致退相干的任何自由度隔离开来。如果量子比特是在半导体中的施主上的自旋，施主自旋可以和宿主材料中其他大量核自旋构成的群体相互作用。因此宿主应该只含有自旋 $I=0$ 的原子核。这个简单的要求遗憾地排除了所有III-V半导体作为宿主的可能性，因为他们中的任何元素都没有稳定的 $I=0$ 的同位素^[21]。而IV半导体主要包含 $I=0$ 同位素，而且理论上可以被提纯到只含有 $I=0$ 的同位素。由于硅材料技术的领先状态以及现阶段人们对硅纳米加工方面的巨大投入，硅理所当然地成为半导体宿主的选择。 [英文](#)

硅中唯一的 $I=1/2$ 浅施主（第五主族）是 ^{31}P 。在40年以前人们发现的第一个电子-原子核双共振的试验中^[22,23] Si^{31}P 系统已经得到了深

入的研究。温度 $T=1.5$ K时，当 ^{31}P 的浓度足够低时，电子自旋的弛豫时间是几千秒， ^{31}P 的核自旋弛豫时间超过10小时。这样的话，在毫开尔文的温度下，声子散射受限的 ^{31}P 的弛豫时间在 10^{18} 秒的量级（文献24），使得这种系统成为量子计算的理想选择。 [英文](#)

该计算机利用电子来促成核自旋之间的相互作用以及核自旋的测量。电子和核自旋之间不可逆的相互作用必须在计算过程中避免：电子必须在整个计算过程中处于非简并基态。在足够低的温度下，通过外加磁场 B 打破电子基态的双重自旋简并度，这样电子只占据施主的最低能量束缚态。（硅的导带的谷简并在施主附近被破坏了^[25]。施主的最低激发态大概是基态上方15 meV^[23]。）当 $2\mu_B B \gg kT$ 时，电子仅占据最低自旋能级，其中 μ_B 是波尔磁子。（在硅中，朗德 g 因子非常接近+2，所以在我们的讨论中使用 $g=2$ 。）当 $T \leq 100$ mK且 $B \geq 2$ T的时候，电子将会被完全自旋极化（ $n_\uparrow/n_\downarrow < 10^{-6}$ ）。量子力学计算机是无耗散的，因此可以在低温状态下运行。然而当栅极偏压出现以及 B_{ac} 引起的涡电流出现时，计算机外部的功耗会上升，这在核自旋的极化和测量时也会出现。这些效应决定了计算机的最低工作温度。为了讨论这些问题，我们假设 $T=100$ mK且 $B=2$ T。注意这些条件并不是完全极化了核自旋，核自旋是通过和极化电子的作用来对齐的。 [英文](#)

在Si: ^{31}P 中的自旋相互作用的量级

自旋相互作用的大小决定了量子比特基本运算所需要的时间以及阵列中施主之间需要的间隔。硅中的核自旋-电子系统的哈密顿量，在施主原子核 $I=1/2$ 、磁场 B 方向平行于 z 方向时，为 $H_{en} = \mu_B B \sigma_{ez} - g_n \mu_n B \sigma_{nz} + A \sigma_e \cdot \sigma_n$ ，这里 σ 是泡利自旋矩阵（本征值为 ± 1 ）， μ_n 是核磁子， g_n 是原子核的 g 因子（对于 ^{31}P 而言， g 因子为1.13；文献21），

$A = \frac{8}{3} \pi \mu_B g_n \mu_n |\Psi(0)|^2$ 是接触超精细相互作用能，其中 $|\Psi(0)|^2$ 是电子波函数在原子核的概率密度。如果电子处于基态，那么原子核能级的频率间隔（取到二阶）是，

$$h\nu_A = 2g_n \mu_n B + 2A + \frac{2A^2}{\mu_B B} \quad (1)$$

在Si: ^{31}P 中， $2A/h = 58$ MHz；在 $B < 3.5$ T的时候，公式（1）中的第二

项大于第一项。 英文

一个施加于电子-施主系统的外加电场会使得电子波函数的包络线向远离原子核的方向平移从而减少超精细相互作用。根据科恩[25]对硅中浅施主斯塔克位移的估测，图2给出了栅极下方200 Å处施主上述位移的大小。靠近“A栅极”的施主核自旋-电子系统起到电压控制振荡器的作用：这样核自旋的进动频率就可以外部控制了，自旋也可以选择性地与 B_{ac} 共振，这就使得每一个核自旋可以任意地旋转。 英文

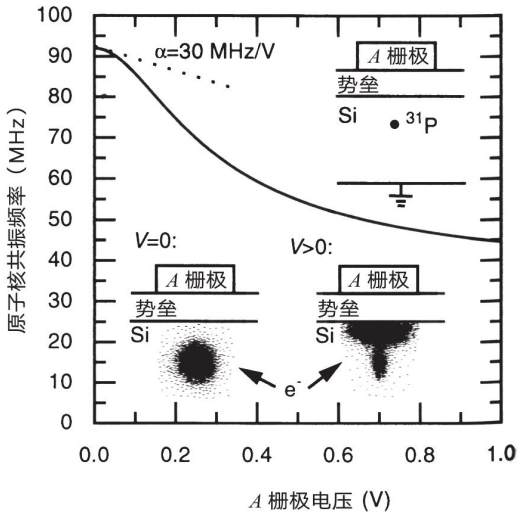


图2．施加于A栅极的电场使得电子波函数远离施主而朝向势垒，这就减少了超精细相互作用以及原子核的共振频率。施主的原子核-电子系统是一个电压调节的振荡器，调谐参数 α 量级为30 MHz·V⁻¹。 英文

除了单个自旋的旋转，量子力学计算需要双量子比特的“控制旋转”操作，当且仅当控制量子比特的取向在特定方向时，该操作将会使目标量子比特的自旋按照指定的角度旋转，从而使得控制量子比特的取向不变[26,27]。要实现这种控制旋转操作需要两个施主原子核-电子自旋系统中的核自旋交换[13]，当两个施主足够接近的时候，这将会由于电子介导相互作用而发生。当能量尺度与施主-电子结合能相比较小的时候，两个耦合的施主原子核-电子系统的哈密顿量可以表示为 $H = H(B) + A_1 \sigma_1^n \cdot \sigma_2^e + A_2 \sigma_2^n \cdot \sigma_2^e + J \sigma_1^e \cdot \sigma_2^e$ 。其中 $H(B)$ 为自旋的磁场相互作用项。 A_1 和 A_2 为两个原子核-电子系统中各自的超精细相互作用能量。 $4J$ 为依赖于电子波函数重叠的交换能。对于足够隔离的施主[28]

而言，

$$4J(r) \cong 1.6 \frac{e^2}{\epsilon a_B} \left(\frac{r}{a_B} \right)^{\frac{5}{2}} \exp \left(\frac{-2r}{a_B} \right) \tag{2}$$

其中 r 是施主之间的距离， ϵ 是半导体的介电常数， a_B 是半导体的玻尔半径。根据硅来选取适当的参数，这个函数的图像如图3所示。起初由氢原子推导出来的公式（2）在硅中是非常复杂的，这是因为硅的谷简并各向异性能带结构^[29]。每一个谷干涉的交换耦合项都会导致 $J(r)$ 的振荡行为。在这里的讨论中，我们将忽略由于硅的能带结构导致的复杂问题。为了在图3中确定 $J(r)$ ，采用硅的横质量（ $\cong 0.2m_e$ ）， $a_B = 30 \text{ \AA}$ 。因为 J 正比于电子波函数的重叠，它会通过施主之间的“ J 栅极”所产生的静电势而变化^[13]。如下所示，当 $4J \approx \mu_B B$ 的时候，核之间会产生显著的耦合，这个已经逼近了施主之间的最小要求间距 $100 \sim 200 \text{ \AA}$ 。然而实际上的间距可能远大于这个值，因为 J 栅极可以被施加正偏压来减少施主之间的势垒，量子计算机所需要的栅极的尺寸已经接近了当今电子学微加工技术的极限。

英文

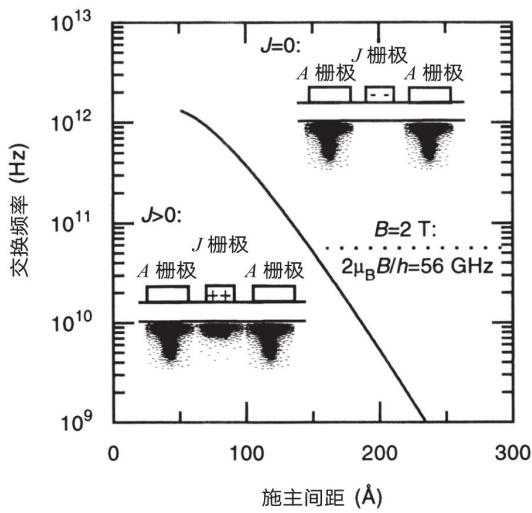


图3 . J 栅极可以改变施主之间的静电势垒 V ，以此来增强或者减弱交换耦合，正比于电子波函数的重叠。当 $V=0$ 时，硅的交换频率（ $4J/h$ ）如图所示。

英文

对于双电子系统来说，交换作用使得电子的单重态 $(|\uparrow\downarrow - \downarrow\uparrow\rangle)$ 能量相对于三重态能量降低^[30]。 $(|\uparrow\downarrow\rangle)$ 符号被用来代表电子自旋态， $|01\rangle$ 符号表示核自旋态；在 $|\downarrow\downarrow 11\rangle$ 状态下，所有自旋在同一方向。为了简

化，归一化的常数被省略)。然而在磁场存在时，当 $J < \mu_B B / 2$ 时（如图4a所示）， $|\downarrow\downarrow\rangle$ 将会是电子的基态。在 $|\downarrow\downarrow\rangle$ 态中，核态的能量可以用微扰理论取到A的二阶项来计算。当 $A_1 = A_2 = A$ 时， $|10-01\rangle$ 态的能量相比 $|10+01\rangle$ 态的能量小了：

$$h\nu_J = 2A^2 \left(\frac{1}{\mu_B B - 2J} - \frac{1}{\mu_B B} \right) \tag{3}$$

$|11\rangle$ 态在 $|10+01\rangle$ 态上方距离能量 $h\nu_A$ 处，而 $|00\rangle$ 在 $|10-01\rangle$ 下方距离能量 $h\nu_A$ 处，由公式（1）给出。对于Si:³¹P系统，在 $B = 2 \text{ T}$ 且 $4J / h = 30 \text{ GHz}$ 时，公式（3）给出解为 $\nu_J = 75 \text{ kHz}$ 。这个核自旋交换频率近似于计算机进行二进制运算的频率（ ν_J 可以通过增加 J 来增加，但是也以增加了耦合原子核-电子自旋激发的弛豫速率为代价）。单个自旋的运算速度是由 B_{ac} 的大小来决定的，当 $B_{ac} = 10^{-3} \text{ T}$ 时相当于75 kHz。

英文

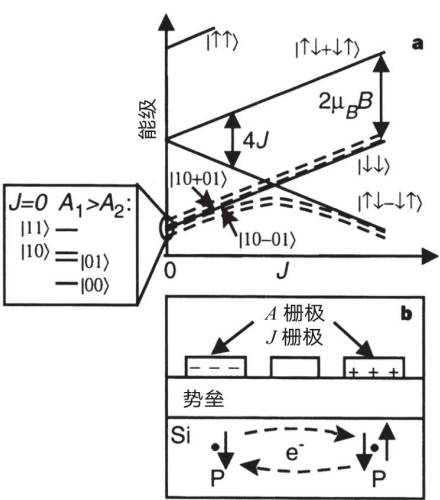


图4．两个量子比特的逻辑和自旋测量。**a**，电子（实线）和最低能量耦合电子-核自旋（虚线）能级随 J 的变化。当 $J < \mu_B B / 2$ ，两个量子比特计算通过使用 J 栅极控制 $|10-01\rangle - |10+01\rangle$ 能级分裂来实现。在 $J = \mu_B B / 2$ 上方，耦合系统的态演化为不同电子极化的态。原子核的具有很大大能量分裂的（受 A 栅极偏压的控制）在 $J = 0$ 的态决定了在 J 绝热增加后，电子最终的自旋态。**b**，只有 $|\uparrow\downarrow - \downarrow\uparrow\rangle$ 电子才可以转换成电子与同一个施主结合的态（ $D^{\cdot}$ 态）。这个转换过程的电子电流是可以通过电容技术来测量的，这就使得电子和原子核的基础自旋态可以被探测。

英文

自旋测量

在本文提出的量子计算机中，核自旋测量是分两步来实现的：不同

的原子核自旋态绝热转化为不同电子极化的态，且电子自旋是由其对交换耦合双电子系统的轨道波函数对称性的影响来决定的。图4展示了如何实现这一转换的过程。当计算完成时 $J < \mu_B B / 2$ 且电子被充分地极化，测量在 $J > \mu_B B / 2$ 时进行， $|\uparrow\downarrow - \downarrow\uparrow\rangle$ 态有最低的能量（图4a）。当电子能级交叉时， $|\downarrow\downarrow\rangle$ 态和 $|\uparrow\downarrow - \downarrow\uparrow\rangle$ 态就会通过与原子核产生超精细相互作用耦合。在 J 绝热增加过程中，当 $J > \mu_B B / 2$ 时，两个处于 $J = 0$ 的低能量核自旋态演化为 $|\uparrow\downarrow - \downarrow\uparrow\rangle$ 态，然而两个高能级的核自旋态仍然保持 $|\downarrow\downarrow\rangle$ 态。如果在 $J = 0$ 时， $A_1 > A_2$ ，1号原子核自旋的取向将独自决定系统在 J 的绝热增加过程中是演化为 $|\uparrow\downarrow - \downarrow\uparrow\rangle$ 态或者是 $|\downarrow\downarrow\rangle$ 态。

英文

一种用来探测电子自旋态的方法是使用电子手段，如图4b所示。如果施主上方的A栅极被施加适当的偏压，两个电子可以都结合到同一个施主（ $D^{\cdot}$ 态）。在Si:P中 $D^{\cdot}$ 态总是具有1.7 meV第二电子结合能的单重态^[31,32]。因此，施加一个差分电压于栅极A上可以导致只有处于单重态的电子可以在施主间产生电荷移动。这种电荷移动可以通过灵敏的单电子电容技术^[33]来测量。这种测量自旋的方法产生的信号持续到电子自旋发生弛豫为止，如前所述，在Si:P系统中这种过程可以有几千秒的时间。

英文

自旋的测量过程也可以用来将核自旋初始化到指定的态上：首先确定自旋的态，如果需要的话就翻转它使它停在想要的自旋态上。正如我们已经讨论的自旋计算过程，自旋的测量和准备原则上可以在计算机中并行执行。

英文

初始化计算机

在进行任何计算之前，计算机必须通过定标A栅极和J栅极来实现初始化。施主位置以及栅极大小的不均匀必然造成不同单元执行逻辑运算所必需的栅极偏压的涨落，不过每个单元的参数都可以通过计算机的测量功能来独自地确定，因为这里讨论的测量技术不需要非常准确地了解J栅极和A栅极的耦合。A栅极下面核自旋与外加 B_{ac} 共振时，所需要施加的A栅极电压可以通过绝热快速通过技术^[34]来确定：当 $B_{ac} = 0$ 时，核自旋被测量，且A栅极被施加一个能消除共振的偏压。 B_{ac} 然后被启动，在

指定的电压区间内扫描A栅极偏压。然后关闭 B_{ac} 并再次测量核自旋。当且仅当共振在指定的A栅极电压范围内出现的时候，自旋才会被翻转。在越来越小的电压范围内测试自旋的翻转将能确定出共振的电压。当邻近的A栅极被定标之后，J栅极可以用同样的方法在两个耦合单元的共振区扫描J栅极偏压来定标。 [英文](#)

这种定标程序可以在多个单元上面并行进行，所以定标问题不是将计算机扩展到大尺寸的主要阻碍。定标电压可以存储在连接到量子计算机上的硅芯片的电容中。因此，外部控制电路只需要控制栅极偏压的时间，而不是他们的大小。 [英文](#)

栅极导致的自旋退相干

在上面概述的量子计算机的设计结构中，对A类和J类栅极施加偏压可以自定义地控制量子比特以及他们之间的相互作用。然而如果栅极的偏压振荡出期望的范围，栅极的存在将导致自旋退相干。这些效应应该在任何通过栅极控制来实现的量子计算机的性能评价中被考虑到。在计算过程中，导致退相干的主要来源一般是A栅极上的电压振荡。（当 $J < \mu_B B / 2$ 时，态能量被J栅极调制的幅度远小于被A栅极调制的幅度。J超过 $\mu_B B / 2$ 只会发生在测量过程，那时退相干是不可避免的。）在 $t=0$ 时刻同相位中的两个自旋的进动频率取决于他们各自A栅极上的电势。这两个电势的差值波动引起进动频率的相对变化。在稍后的 $t=t_\phi$ 时刻，这两个自旋的相位将会相差180度（反相位）； t_ϕ 可以通过这个双自旋系统在 $|10+01\rangle$ （自旋同相位）和 $|10-01\rangle$ （自旋180度反相位）两种状态间的转换速率来确定。这些态之间耦合的哈密顿量为

$H_\phi = \frac{1}{4} \hbar \Delta (\sigma_z^{1n} - \sigma_z^{2n})$ ，其中 Δ 是不同自旋进动频率差值的振荡。对该振荡哈密顿量进行标准处理^[34]导出： $t_\phi^{-1} = \pi^2 S_\Delta(v_{st})$ ，其中 S_Δ 是频率振荡的频谱密度， v_{st} 是 $|10-01\rangle$ 和 $|10+01\rangle$ 态之间的频率差。在一个固定的偏压下，A类栅极有一个频率调谐参数 $\alpha = d\Delta / dV$ 。因此

$$t_\phi^{-1} = \pi^2 \alpha^2(V) S_V(v_{st}) \quad (4)$$

其中 S_V 是栅极电压涨落的频谱密度。 [英文](#)

良好的室温电子元件的 S_V 的量级是 $10^{-18} \text{ V}^2 / \text{Hz}$ ，这和一个 $50 \text{ } \Omega$ 的电阻的室温约翰逊噪音是接近的。从图2中估算出的 α 值大概为 $10 \sim 100 \text{ MHz} \cdot \text{V}^{-1}$ ，导出 $t_\phi = 10 \sim 1,000 \text{ s}$ ； α 可以由施主阵列单元的大小来确定，且不能在不减小单元之间的相互作用的情况下被轻易地减小（来增加 t_ϕ ）。因为 α 是栅极偏压的函数（图2）， t_ϕ 可以通过最小化A类栅极偏压来增加。 [英文](#)

虽然公式4对白噪声来说是正确的，在低频率条件下，导致自旋退相的主要原因很可能是依赖于材料的波动（ $1 / f$ 噪音）。因此给出计算机一个准确的预期值 t_ϕ 是非常困难的。计算机内部的电荷涨落（例如由陷阱和表面态的占位数涨落引起）很可能是非常重要的，这就要求在计算机制造中最小化这种电荷涨落。 [英文](#)

虽然依赖材料的波动很难预期，在低温条件下的计算机运算以及量子计算无耗散的特征意味着，原则上波动可以被保持得很小：使用低温电子器件来给栅极施加偏压（例如之前讨论中提到的使用芯片电容）可以使得 t_ϕ 约等于 10^6 s 。电子器件控制的核自旋量子计算机因此理论上具备了在 t_ϕ 时间内执行 10^5 到 10^{10} 逻辑运算的能力，这样基本上就满足了普雷斯基尔的每个量子比特运算误码率为 10^{-6} 的准则^[8]。 [英文](#)

构造计算机

构造一个这里讨论的计算机显然将是非常巨大的挑战：选取的材料必须完全没有自旋（ $I \neq 0$ 同位素）和电荷杂质，以避免计算机中出现退相位扰动。施主必须作为一个有序的阵列导入材料表面几百埃以下。最后，横向尺寸和间距为 $100 \text{ } \text{\AA}$ 左右的栅极被加工在表面，与其下方的施主对应。虽然使用二氧化硅（大多数当前传统电子器件所使用的标准MOS技术）作为势垒层材料是可行的，但是由于需要最小化无序和扰动，意味着异质外延材料如硅/硅锗（Si/SiGe）最终可能优于硅/二氧化硅（Si/SiO₂）。 [英文](#)

构造上文描述的量子计算机最明显的困难是如何将施主阵列注入势垒层下方的硅层中。现阶段半导体结构是逐层沉积制造的。 δ 掺杂技术得到的施主位于材料中的单层中，其中施主是随机分布在这一层中的。

我们这里设想的量子计算机要求施主被放置于有序的一维或者二维的阵列中；另外，施主必须被准确地放置在每个阵列单元中，这就使得通过光刻技术和离子注入或者通过聚焦沉积方法都很难制造出这种阵列。目前正在发展的将单原子放在表面的技术是利用超高真空扫描隧道显微镜^[35]或者原子光学技术^[36]实现的，这些是可能被用来放置施主阵列的备选方法。接着的一个挑战将是在施主放置处表面上生长高质量的硅层。

英文

制造大的施主阵列也许是非常困难的，但是用来检验此处介绍的逻辑计算和测量技术的双自旋器件可以使用随机掺杂技术来制造。虽然只有一小部分这样的器件可以正常工作，但是相关的传统硅电子学中的复用电路可以用来独立地检测许多器件。制造这种“混合”（量子-传统）电路的相对简易性是硅基量子计算机的独特魅力所在。

英文

在基于硅的核自旋量子计算机中，量子计算所必需的高度相干的量子态被整合到能够实现复杂计算机结构的材料中。实现量子计算机面临的重要挑战，尤其是100 Å尺度的栅极器件制造，与下一代传统电子器件面临的挑战类似；因此，正为传统电子器件研发的新制造技术将与开发硅量子计算机的努力直接相关。足够复杂以至于可以实现其理论潜力的量子计算机，也许会在将来的某一天使用传统计算机类似的技术搭建起来。

英文

（姜克 翻译；杜江峰 审稿）

Collective Dynamics of “Small-world” Networks

D. J. Watts and S. H. Strogatz

We live in a world of networks, from human social networks and biological food webs to neural systems, transportation networks and the modern Internet. In this paper, Duncan Watts and Steven Strogatz demonstrate that these networks often share surprising architectural similarities. Most notably, they are “small worlds”, in that only a few steps are needed to move along links from any one point to another, even in networks containing an enormous number of elements. Such networks also tend to be highly “clustered”, with many redundant paths, making them connected wholes that are resilient to the removal of links. This paper stimulated an explosion of work on complex networks by providing a new conceptual framework for analysing them.

[中文](#)

Networks of coupled dynamical systems have been used to model biological oscillators¹⁻⁴, Josephson junction arrays^{5,6}, excitable media⁷, neural networks⁸⁻¹⁰, spatial games¹¹, genetic control networks¹² and many other self-organizing systems. Ordinarily, the connection topology is assumed to be either completely regular or completely random. But many biological, technological and social networks lie somewhere between these two extremes. Here we explore simple models of networks that can be tuned through this

middle ground: regular networks “rewired” to introduce increasing amounts of disorder. We find that these systems can be highly clustered, like regular lattices, yet have small characteristic path lengths, like random graphs. We call them “small-world” networks, by analogy with the small-world phenomenon^{13,14} (popularly known as six degrees of separation¹⁵). The neural network of the worm *Caenorhabditis elegans*, the power grid of the western United States, and the collaboration graph of film actors are shown to be small-world networks. Models of dynamical systems with small-world coupling display enhanced signal-propagation speed, computational power, and synchronizability. In particular, infectious diseases spread more easily in small-world networks than in regular lattices. [中文](#)

To interpolate between regular and random networks, we consider the following random rewiring procedure (Fig. 1). Starting from a ring lattice with n vertices and k edges per vertex, we rewire each edge at random with probability p . This construction allows us to “tune” the graph between regularity ($p=0$) and disorder ($p=1$), and thereby to probe the intermediate region $0 < p < 1$, about which little is known.

[中文](#)

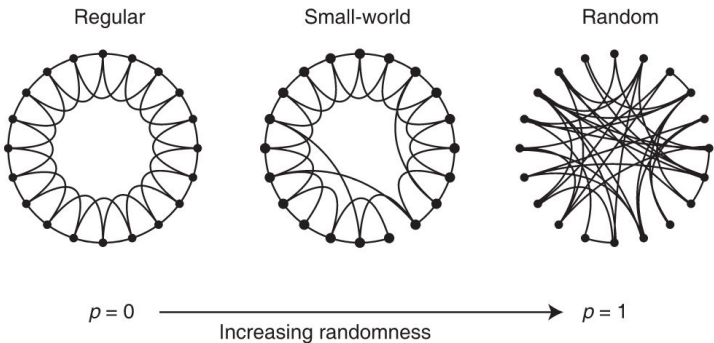


Fig. 1. Random rewiring procedure for interpolating between a regular ring lattice and a random network, without altering the number of vertices or edges in the graph. We start with a ring of n vertices, each connected to its k nearest neighbours by undirected edges. (For clarity, $n = 20$ and $k = 4$ in the schematic examples shown here, but much larger n and k are

used in the rest of this Letter.) We choose a vertex and the edge that connects it to its nearest neighbour in a clockwise sense. With probability p , we reconnect this edge to a vertex chosen uniformly at random over the entire ring, with duplicate edges forbidden; otherwise we leave the edge in place. We repeat this process by moving clockwise around the ring, considering each vertex in turn until one lap is completed. Next, we consider the edges that connect vertices to their second-nearest neighbours clockwise. As before, we randomly rewired each of these edges with probability p , and continue this process, circulating around the ring and proceeding outward to more distant neighbours after each lap, until each edge in the original lattice has been considered once. (As there are $nk/2$ edges in the entire graph, the rewiring process stops after $k / 2$ laps.) Three realizations of this process are shown, for different values of p . For $p=0$, the original ring is unchanged; as p increases, the graph becomes increasingly disordered until for $p=1$, all edges are rewired randomly. One of our main results is that for intermediate values of p , the graph is a small-world network: highly clustered like a regular graph, yet with small characteristic path length, like a random graph. (See Fig. 2.)

中文

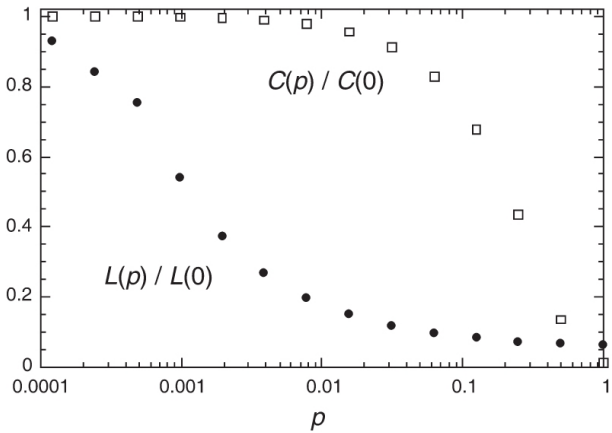


Fig. 2. Characteristic path length $L(p)$ and clustering coefficient $C(p)$ for the family of randomly rewired graphs described in Fig. 1. Here L is defined as the number of edges in the shortest path between two vertices, averaged over all pairs of vertices. The clustering coefficient $C(p)$ is defined as follows. Suppose that a vertex v has k_v neighbours; then at most $k_v (k_v - 1) / 2$ edges can exist between them (this occurs when every neighbour of v is connected to every other neighbour of v). Let C_v denote the fraction of these allowable edges that actually exist. Define C as the average of C_v over all v . For friendship networks, these statistics have intuitive meanings: L is the average number of friendships in the shortest chain connecting two people; C_v reflects the extent to which friends of v are also friends of each other; and thus C measures the cliquishness of a typical friendship circle. The data shown in the figure are averages over 20 random realizations of the rewiring process described in Fig. 1, and have been normalized by the values $L(0)$, $C(0)$ for a regular lattice. All the graphs have $n=1,000$ vertices and an average degree of $k=10$ edges per vertex. We note that a logarithmic horizontal scale has been used to resolve the rapid drop in $L(p)$, corresponding to the onset of the small-world phenomenon. During this drop, $C(p)$ remains almost constant at

its value for the regular lattice, indicating that the transition to a small world is almost undetectable at the local level. [中文](#)

We quantify the structural properties of these graphs by their characteristic path length $L(p)$ and clustering coefficient $C(p)$, as defined in Fig. 2 legend. Here $L(p)$ measures the typical separation between two vertices in the graph (a global property), whereas $C(p)$ measures the cliquishness of a typical neighbourhood (a local property). The networks of interest to us have many vertices with sparse connections, but not so sparse that the graph is in danger of becoming disconnected. Specifically, we require $n \gg k \gg \ln(n) \gg 1$, where $k \gg \ln(n)$ guarantees that a random graph will be connected¹⁶. In this regime, we find that $L \sim n / 2k \gg 1$ and $C \sim 3 / 4$ as $p \rightarrow 0$, while $L \approx L_{\text{random}} \sim \ln(n) / \ln(k)$ and $C \approx C_{\text{random}} \sim k / \ll 1$ as $p \rightarrow 1$. Thus the regular lattice at $p=0$ is a highly clustered, large world where L grows linearly with n , whereas the random network at $p=1$ is a poorly clustered, small world where L grows only logarithmically with n . These limiting cases might lead one to suspect that large C is always associated with large L , and small C with small L . [中文](#)

On the contrary, Fig. 2 reveals that there is a broad interval of p over which $L(p)$ is almost as small as L_{random} yet $C(p) \gg C_{\text{random}}$. These small-world networks result from the immediate drop in $L(p)$ caused by the introduction of a few long-range edges. Such “short cuts” connect vertices that would otherwise be much farther apart than L_{random} . For small p , each short cut has a highly nonlinear effect on L , contracting the distance not just between the pair of vertices that it connects, but between their immediate neighbourhoods, neighbourhoods of neighbourhoods and so on. By contrast, an edge removed from a clustered neighbourhood to make a short cut has, at most, a linear effect on C ; hence $C(p)$ remains practically unchanged for small p even though $L(p)$ drops rapidly. The important implication here is that at the local level (as reflected by $C(p)$), the transition to a small world is almost undetectable. To check the robustness of these

results, we have tested many different types of initial regular graphs, as well as different algorithms for random rewiring, and all give qualitatively similar results. The only requirement is that the rewired edges must typically connect vertices that would otherwise be much farther apart than L_{random} . 中文

The idealized construction above reveals the key role of short cuts. It suggests that the small-world phenomenon might be common in sparse networks with many vertices, as even a tiny fraction of short cuts would suffice. To test this idea, we have computed L and C for the collaboration graph of actors in feature films (generated from data available at <http://us.imdb.com>), the electrical power grid of the western United States, and the neural network of the nematode worm *C. elegans*¹⁷. All three graphs are of scientific interest. The graph of film actors is a surrogate for a social network¹⁸, with the advantage of being much more easily specified. It is also akin to the graph of mathematical collaborations centred, traditionally, on P. Erdős (partial data available at <http://www.acs.oakland.edu/~grossman/erdoshp.html>). The graph of the power grid is relevant to the efficiency and robustness of power networks¹⁹. And *C. elegans* is the sole example of a completely mapped neural network. 中文

Table 1 shows that all three graphs are small-world networks. These examples were not hand-picked; they were chosen because of their inherent interest and because complete wiring diagrams were available. Thus the small-world phenomenon is not merely a curiosity of social networks^{13,14} nor an artefact of an idealized model—it is probably generic for many large, sparse networks found in nature.

中文

Table 1. Empirical examples of small-world networks

	L_{actual}	L_{random}	C_{actual}	C_{random}
Film actors	3.65	2.99	0.79	0.00027
Power grid	18.7	12.4	0.080	0.005
<i>C. elegans</i>	2.65	2.25	0.28	0.05

Characteristic path length L and clustering coefficient C for three real networks, compared to random graphs with the same number of vertices (n) and average number of edges per vertex (k). (Actors: $n = 225,226$, $k = 61$. Power grid: $n = 4,941$, $k = 2.67$. *C. elegans*: $n = 282$, $k = 14$.) The graphs are defined as follows. Two actors are joined by an edge if they have acted in a film together. We restrict attention to the giant connected component¹⁶ of this graph, which includes $\sim 90\%$ of all actors listed in the Internet Movie Database (available at <http://us.imdb.com>), as of April 1997. For the power grid, vertices represent generators, transformers and substations, and edges represent high-voltage transmission lines between them. For *C. elegans*, an edge joins two neurons if they are connected by either a synapse or a gap junction. We treat all edges as undirected and unweighted, and all vertices as identical, recognizing that these are crude approximations. All three networks show the small-world phenomenon: $L \geq L_{\text{random}}$ but $C \gg C_{\text{random}}$. 中文

We now investigate the functional significance of small-world connectivity for dynamical systems. Our test case is a deliberately simplified model for the spread of an infectious disease. The population structure is modelled by the family of graphs described in Fig. 1. At time $t = 0$, a single infective individual is introduced into an otherwise healthy population. Infective individuals are removed permanently (by immunity or death) after a period of sickness that lasts one unit of dimensionless time. During this time, each infective individual can infect each of its healthy neighbours with probability r . On subsequent time steps, the disease spreads along the edges of the graph until it either infects the entire population, or it dies out, having infected some fraction of the population in the process. 中文

Two results emerge. First, the critical infectiousness r_{half} , at which the disease infects half the population, decreases rapidly for small p (Fig. 3a). Second, for a disease that is sufficiently infectious to infect the entire population regardless of its structure, the time $T(p)$ required for global infection resembles the $L(p)$ curve (Fig. 3b). Thus, infectious diseases are predicted to spread much more easily and quickly in a small world; the alarming and less obvious point is how few short cuts

are needed to make the world small. 中文

Our model differs in some significant ways from other network models of disease spreading²⁰⁻²⁴. All the models indicate that network structure influences the speed and extent of disease transmission, but our model illuminates the dynamics as an explicit function of structure (Fig. 3), rather than for a few particular topologies, such as random graphs, stars and chains²⁰⁻²³. In the work closest to ours, Kretschmar and Morris²⁴ have shown that increases in the number of concurrent partnerships can significantly accelerate the propagation of a sexually-transmitted disease that spreads along the edges of a graph. All their graphs are disconnected because they fix the average number of partners per person at $k=1$. An increase in the number of concurrent partnerships causes faster spreading by increasing the number of vertices in the graph's largest connected component. In contrast, all our graphs are connected; hence the predicted changes in the spreading dynamics are due to more subtle structural features than changes in connectedness. Moreover, changes in the number of concurrent partners are obvious to an individual, whereas transitions leading to a smaller world are not. 中文

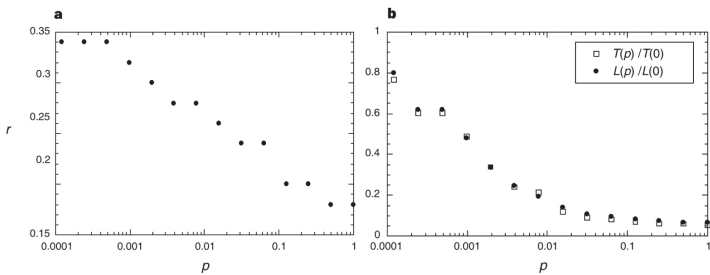


Fig. 3. Simulation results for a simple model of disease spreading. The community structure is given by one realization of the family of randomly rewired graphs used in Fig. 1. **a**, Critical infectiousness r_{half} , at which the disease infects half the population, decreases with p . **b**, The time $T(p)$ required for a maximally infectious disease ($r=1$) to spread throughout the entire population has essentially the same functional form as the characteristic path length $L(p)$. Even if only a few per cent of the edges in the original lattice are randomly rewired, the time to global infection is nearly as short as for a random graph. 中文

We have also examined the effect of small-world connectivity on three

other dynamical systems. In each case, the elements were coupled according to the family of graphs described in Fig. 1. (1) For cellular automata charged with the computational task of density classification²⁵, we find that a simple “majority-rule” running on a small-world graph can outperform all known human and genetic algorithm-generated rules running on a ring lattice. (2) For the iterated, multi-player “Prisoner’s dilemma”¹¹ played on a graph, we find that as the fraction of short cuts increases, cooperation is less likely to emerge in a population of players using a generalized “tit-for-tat”²⁶ strategy. The likelihood of cooperative strategies evolving out of an initial cooperative / non-cooperative mix also decreases with increasing p . (3) Small-world networks of coupled phase oscillators synchronize almost as readily as in the mean-field model², despite having orders of magnitude fewer edges. This result may be relevant to the observed synchronization of widely separated neurons in the visual cortex²⁷ if, as seems plausible, the brain has a small-world architecture. 中文

We hope that our work will stimulate further studies of small-world networks. Their distinctive combination of high clustering with short characteristic path length cannot be captured by traditional approximations such as those based on regular lattices or random graphs. Although small-world architecture has not received much attention, we suggest that it will probably turn out to be widespread in biological, social and man-made systems, often with important dynamical consequences. 中文

(393, 440-442; 1998)

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Received 27 November 1997; accepted 6 April 1998.

References:

1. Winfree, A. T. *The Geometry of Biological Time* (Springer, New York, 1980).
2. Kuramoto, Y. *Chemical Oscillations, Waves, and Turbulence* (Springer, Berlin, 1984).
3. Strogatz, S. H. & Stewart, I. Coupled oscillators and biological synchronization. *Sci. Am.* **269**(6), 102-109 (1993).
4. Bressloff, P. C., Coombes, S. & De Souza, B. Dynamics of a ring of pulse-coupled oscillators: a group theoretic approach. *Phys. Rev. Lett.* **79**, 2791-2794 (1997).
5. Braiman, Y., Lindner, J. F. & Ditto, W. L. Taming spatiotemporal chaos with disorder. *Nature* **378**, 465-467 (1995).
6. Wiesenfeld, K. New results on frequency-locking dynamics of disordered Josephson arrays. *Physica B* **222**, 315-319 (1996).
7. Gerhardt, M., Schuster, H. & Tyson, J. J. A cellular automaton model of excitable media including curvature and dispersion. *Science* **247**, 1563-1566 (1990).
8. Collins, J. J., Chow, C. C. & Imhoff, T. T. Stochastic resonance without tuning. *Nature* **376**, 236-238 (1995).
9. Hopfield, J. J. & Herz, A. V. M. Rapid local synchronization of action potentials: Toward computation with coupled integrate-and-fire neurons. *Proc. Natl Acad. Sci. USA* **92**, 6655-6662 (1995).
10. Abbott, L. F. & van Vreeswijk, C. Asynchronous states in neural networks of pulse-coupled oscillators. *Phys. Rev. E* **48**(2), 1483-1490 (1993).
11. Nowak, M. A. & May, R. M. Evolutionary games and spatial chaos. *Nature* **359**, 826-829 (1992).
12. Kauffman, S. A. Metabolic stability and epigenesis in randomly constructed genetic nets. *J. Theor. Biol.* **22**, 437-467 (1969).
13. Milgram, S. The small world problem. *Psychol. Today* **2**, 60-67 (1967).
14. Kochen, M. (ed.) *The Small World* (Ablex, Norwood, NJ, 1989).
15. Guare, J. *Six Degrees of Separation: A Play* (Vintage Books, New York, 1990).
16. Bollabás, B. *Random Graphs* (Academic, London, 1985).
17. Achacoso, T. B. & Yamamoto, W. S. *AY's Neuroanatomy of C. elegans for Computation* (CRC Press, Boca Raton, FL, 1992).
18. Wasserman, S. & Faust, K. *Social Network Analysis: Methods and Applications* (Cambridge Univ. Press, 1994).
19. Phadke, A. G. & Thorp, J. S. *Computer Relaying for Power Systems* (Wiley, New York, 1988).
20. Sattenspiel, L. & Simon, C. P. The spread and persistence of infectious diseases in structured populations. *Math. Biosci.* **90**, 341-366 (1988).
21. Longini, I. M. Jr A mathematical model for predicting the geographic spread of new infectious agents. *Math. Biosci.* **90**, 367-383 (1988).
22. Hess, G. Disease in metapopulation models: implications for conservation. *Ecology* **77**, 1617-1632 (1996).
23. Blythe, S. P., Castillo-Chavez, C. & Palmer, J. S. Toward a unified theory of sexual mixing and pair formation. *Math. Biosci.* **107**, 379-405 (1991).

24. Kretschmar, M. & Morris, M. Measures of concurrency in networks and the spread of infectious disease. *Math. Biosci.* **133**, 165-195 (1996).
25. Das, R., Mitchell, M. & Crutchfield, J. P. in *Parallel Problem Solving from Nature* (eds Davido, Y., Schwefel, H.-P. & Männer, R.) 344-353 (Lecture Notes in Computer Science 866, Springer, Berlin, 1994).
26. Axelrod, R. *The Evolution of Cooperation* (Basic Books, New York, 1984).
27. Gray, C. M., König, P., Engel, A. K. & Singer, W. Oscillatory responses in cat visual cortex exhibit intercolumnar synchronization which reflects global stimulus properties. *Nature* **338**, 334-337 (1989).

Acknowledgements. We thank B. Tjaden for providing the film actor data, and J. Thorp and K. Bae for the Western States Power Grid data. This work was supported by the US National Science Foundation (Division of Mathematical Sciences).

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“小世界”网络的集体动力学

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我们生活在一个网络世界里：从人类社会网络和生物食物网到神经系统、运输网络和现代互联网。本文中，邓肯·沃茨和史蒂文·斯特罗加茨证明了这些网络通常具有惊人的结构相似性。最值得注意的是，它们是“小世界”，因为即使在包含大量元素的网络中，也只需要几个步骤就可以沿着链路从一个点移动到另一个点。这种网络也倾向于高度“集群化”，许多冗余路径使得它们连接在一起成为一个整体，从而对链路的移除具有恢复力。本文提供了一个新的概念框架来分析复杂网络，促进了复杂网络研究工作的爆炸式增长。

[英文](#)

耦合动力系统网络已被广泛应用于生物振荡^[1-4]、约瑟夫森结阵列^[5,6]、可激发介质^[7]、神经网络^[8-10]、空间博弈^[11]、基因控制网络^[12]以及多种其他自组织系统的建模。通常情况下，其拓扑结构被认为或是完全规则的，或是完全随机的。但是许多生物、技术和社会的网络介于这两种极端状况之间。本文阐述了一种处于这种中间态的简单的网络模型：将规则网络“重新连接”来引入更多无序性。我们发现这些系统可以像有序晶格一样被高度集聚，同时具有很小的特征路径长度，类似随机图。通过与小世界现象^[13,14]（人们所熟知的六度分隔^[15]）的类比，我们称它们为“小世界”网络。秀丽隐杆线虫的神经网络、美国西部的电力网络以及电影演员的合作图都表现为小世界网络。具有小世界耦合的动力系统模型显示了更强的信号传播速度、计算能力和同步性。特别需要指出的是，传染病在小世界网络中传播要比在规则网络中传播更容易。

[英文](#)

为了实现规则网络和随机网络之间的中间状态，我们来考虑以下的随机重连过程（图1）。从一个具有 n 个顶点，每个顶点 k 条边的环形晶格网络开始，我们以概率 p 随机地将每条边重新连接。这种构造允许我们在规则（ $p=0$ ）和无序（ $p=1$ ）之间“调谐”，从而探索目前被了解得很少的 $0 < p < 1$ 的中间区域。 [英文](#)

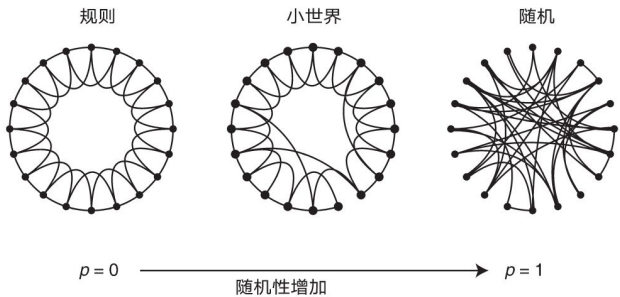


图1．随机重新连接来制造处于规则环形晶格网络和随机网络之间的状态，而顶点和边的数量不变。我们从一个具有 n 个顶点的环开始，每个顶点都与最近的 k 个相邻顶点通过无向边相连。（为了表述清晰，图中的例子取 $n=20$ ， $k=4$ ，但在文中的其他部分我们取了更大的 n 和 k 值。）我们选取一个顶点以及顺时针方向上连接该顶点和最近邻点的边。以概率 p 将这条边重新连接到整个环上随机选取的任一顶点，不允许有重复连接的边；否则保持该边不动。我们沿环的顺时针方向重复这个过程，按顺序考虑到每个顶点直到一圈完成。接下来，我们考虑连接顶点与其顺时针方向第二近邻点的边。像上次操作一样，我们以概率 p 随机地重新连接这些边，然后我们重复这个过程，沿环循环，并在每一圈之后对连接更远近邻点的边继续该操作，直到每条原始网络中的边都被考虑到为止。（因为整个图中共有 $nk/2$ 条边，所以重新连接过程在 $k/2$ 圈后结束。）图中表示了不同 p 时，该过程的三种实现方式。 $p=0$ 时，原始环不变；随 p 增大图形无序性开始增加，到 $p=1$ 时，所有的边都被随机地重新连接。我们得出的一个主要结论是，对于 p 处于中间值时，图为一小世界网络：像规则图一样高度集聚，又像随机图一样具有很小的特征路径长度。（见图2） [英文](#)

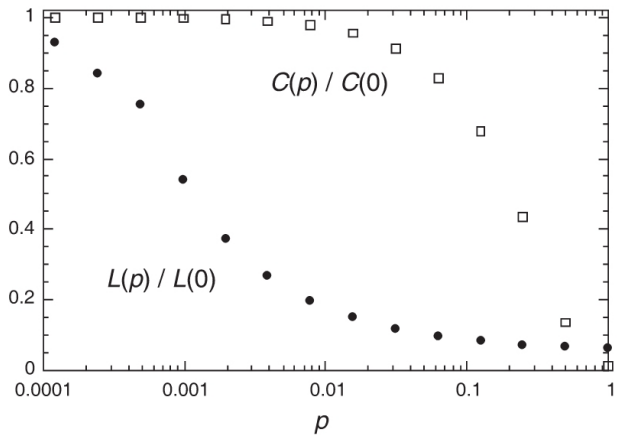


图2．特征路径长度 $L(p)$ 与图1中所描述的随机重连图形的集聚系数 $C(p)$ 的关系。 L 被定义为两

顶点之间最短路径上的边的数量，为所有顶点对的平均值。集聚系数 $C(p)$ 按下述定义。假设一顶点 v 有 k_v 个邻点；那么至多有 $k_v(k_v - 1) / 2$ 条边连接它们（这种情况发生在 v 的每个邻点都与 v 的所有其他邻点相连）。用 C_v 来表示真正存在的边占这些所有被允许出现的边的比例。定义 C 为所有的顶点 v 对应 C_v 的平均值。对于朋友关系网络，这些统计数据有着直观的含义： L 为两个人之间最短链中朋友关系的平均数； C_v 反映 v 的朋友中有多少互相之间也是朋友；因而 C 测量朋友关系圈的小集团性。图中所示的数据为图1中所描述的20种随机重连过程的平均值，并相对规则晶格网络的 $L(0)$ 和 $C(0)$ 进行了归一化。所有的图形都有 $n=1,000$ 个顶点，每个顶点平均有 $k=10$ 条边。我们使用对数横坐标以解决 $L(p)$ 骤降的问题，对应小世界现象的开始。在这个骤降过程中，规则晶格网络的 $C(p)$ 基本保持不变，也就意味着网络结构向小世界的转变在局域上是无法探测的。 英文

通过它们的特征路径长度 $L(p)$ 和集聚系数 $C(p)$ （图2注给出了这两项的定义），我们将这些图形的结构属性进行量化。这里 $L(p)$ 测量图形中两顶点之间的分隔（一种全局属性），而 $C(p)$ 测量近邻顶点间的小集团性（一种局域属性）。我们感兴趣的网络有很多顶点但连接很稀疏，但是没有稀疏到存在使图断开的危险。具体地讲，我们要求 $n \gg k \gg \ln(n) \gg 1$ ，其中 $k \gg \ln(n)$ 确保了随机图会被连接^[16]。在这种机制下，我们发现当 $p \rightarrow 0$ 时， $L \sim n / 2k \gg 1$ ， $C \sim 3 / 4$ ，而当 $p \rightarrow 1$ 时， $L \approx L_{\text{随机}} \sim \ln(n) / \ln(k)$ ， $C \approx C_{\text{随机}} \sim k / n \ll 1$ 。因此在 $p = 0$ 时的规则晶格网络是一高度群聚、 L 随 n 线性增加的大世界，而 $p = 1$ 时的随机网络是一低群聚、 L 只随 n 对数增长的小世界。这些带有限制性的情况很可能让人们认为大的 C 永远与大 L 相关，而小 C 与小 L 相关。 英文

相反地，图2揭示了在 $L(p)$ 小到与 $L_{\text{随机}}$ 接近，但 $C(p) \gg C_{\text{随机}}$ 时， p 存在一个很宽的跨度。这些小世界网络源于由若干远程边的引入而引起的 $L(p)$ 的骤降。这样的“捷径”连接起了原本要相隔较 $L_{\text{随机}}$ 远很多的顶点。对于小的 p 来说，每一条捷径都产生很强的非线性效应作用于 L ，不仅仅缩短了它所连接的顶点之间的距离，而且还缩短了它们与直接邻点之间的距离，以及与邻点的邻点之间的距离，等等。相比之下，从群聚的邻点中移除用于制造捷径的一条边，最多产生线性效应作用于 C ；因此对于小的 p 即使 $L(p)$ 迅速减小， $C(p)$ 也仍保持不变。这里的一个很重要的启示是，就局部而言（通过 $C(p)$ 所反应的），向小世界的转变几乎无法探测。为了检验这些结果的稳健性，我们测试了多种不同类型的初始规则图，以及随机重连的不同算法，所有的测试都给出性质类似的结果。唯一的要求是重新连接的边通常必须连接原本比 $L_{\text{随机}}$ 远很多的顶点。

英文

以上理想的构造揭示了捷径的核心作用。它意味着小世界现象在多个顶点的稀疏网络中很普遍，很少的捷径就满足要求。为了验证这个想法，我们计算了故事片电影中演员的合作图（数据由<http://us.imdb.com>提供）、美国西部的电力网络以及秀丽隐杆线虫神经网络^[17]这三个图的 L 和 C 。所有这三个图都引起了科学界的兴趣。电影演员合作图是社会网络的代表^[18]，具有很容易被细化定义的优势。它也与传统上的、以保罗·埃尔德什为中心的数学合作图相似（部分数据可以在<http://www.acs.oakland.edu/~grossman/erdoshp.html>上获得）。电力网络的图与电力网络的效率和稳定性相关^[19]。而秀丽隐杆线虫是完整的神经网络的唯一例子。 英文

表1显示所有三个图都是小世界网络。这些例子不是特别挑选出来的；它们之所以被选择是因为它们本身具有吸引力，而且它们的连接完备清晰。因此小世界现象不只是社会网络的奇异现象^[13,14]，也不是一个理想模型的人为性质——它很可能是自然中发现的许多大的、稀疏的网络的普遍现象。 英文

表1. 小世界网络的实际举例

	$L_{\text{真实}}$	$L_{\text{随机}}$	$C_{\text{真实}}$	$C_{\text{随机}}$
电影演员	3.65	2.99	0.79	0.00027
电力网络	18.7	12.4	0.080	0.005
秀丽隐杆线虫	2.65	2.25	0.28	0.05

三个真实网络的特征路径长度 L 和集聚系数 C ，与具有相同的顶点数（ n ）及每顶点的平均边数（ k ）的随机图的比较。（电影演员： $n=225,226, k=61$ 。电力网络： $n=4,941, k=2.67$ 。秀丽隐杆线虫： $n=282, k=14$ 。）图的定义如下。两演员如果出演过同一电影，他们即被一边连接。我们仅关注其中的最大连通子集^[16]，其中包含了截至1997年4月网络电影数据库（源自<http://us.imdb.com>）所列出的所有演员的约90%。对于电力网络，顶点代表发电机、变压器和变电站，边代表他们之间的高压电线。对于秀丽隐杆线虫，如果两神经元通过突触或者缝隙连接相连，则用边将二者连接。我们假设所有的边无方向无加权，所有的顶点都是相同的，所以这只是一种粗糙的近似。所有三个网络显示出小世界现象： $L \geq L_{\text{随机}}$ 而 $C \gg C_{\text{随机}}$ 。 英文

我们现在来研究以小世界方式连接的动力学系统的功能意义。我们的测试案例是被有意简化的一传染性疾病的传播模型。人口的相互作用结构用图1所描述的一系列图给出。在时间 $t=0$ 时，一感染性个体被引入原本健康的人群。被感染的个体在患病经过一无量纲时间单位后被永久性移除（通过免疫或死亡）。在这段时间内，每个被感染的个体以概率 r

传染每个健康的邻居。在随后的时间段，疾病沿图的边传播直到把疾病传染给所有的人，或者疾病传染一部分人之后消亡。[英文](#)

这里出现了两个结果。首先，考查疾病传染一半人口的临界感染率 $r_{\text{半数}}$ ，在 p 较小时，它迅速减小（图3a）。其次，无论什么结构，对于足以传染整个人群的疾病，整体感染所需要的时间 $T(p)$ 与 $L(p)$ 曲线相似（图3b）。因此，传染性疾病可能会更容易、更迅速地在小世界中传播；需要注意但不太明显的一点是最少需要多少捷径可以构造这样的小世界。[英文](#)

我们的模型与其他疾病传播的网络模型^[20-24]有很大程度的不同。其他所有的模型都显示网络结构影响疾病传播的速度和程度，但是我们的模型给出了动力学行为作为结构性质的一个明确函数关系（图3），而不是只考虑少数的特定拓扑结构，例如随机图、星形网络和链^[20-23]。与我们最接近的研究中，克雷奇马尔和莫里斯^[24]已经指出并行性伴侣关系数目的增加会加速沿图边传播的性疾病的传染。他们所有的图形都是断开的，因为他们设定了每个人的伴侣平均数为 $k=1$ 。并行性伴侣关系数目的增加会通过增加最大连通集团中顶点的数目引起传播加速。相比而言，我们的图是相连的；因此所预测的传播动态行为上的改变是由于更多的精细结构特征而非连通性的改变。此外，并行性伴侣关系数目的改变对于个体来说影响是明显的，但对整体结构向小世界转变的影响却不明显。[英文](#)

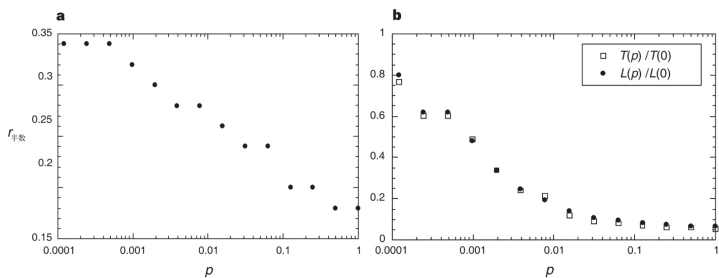


图3．一个简单的疾病传播模型的模拟结果。社群结构由图1中随机重连图族的一个实现给出。**a**，疾病感染半数人群的临界感染率 $r_{\text{半数}}$ 随 p 减小。**b**，最强感染性疾病（ $r=1$ ）传播至整个人群所需的时间 $T(p)$ 具有与特征路径长度 $L(p)$ 相同的函数形式。即使原始晶格网络中只有几个百分比的边被重连，整体感染的时间也与随机图中的一样短。[英文](#)

我们也测试了小世界性质在其他三个动态系统中的效应。在每种情

况下，元素通过图1所描述的系统网络发生耦合。（1）对于负责密度分类计算的元胞自动机^[25]，我们发现一个简单的在小世界图中运行的“多数规则”可以胜过所有已知在环形晶格网络中运行的人为以及遗传算法产生的规则。（2）对于一个基于网络迭代的、多人的“囚徒困境”^[11]，我们发现随捷径数量的增加，运用“以牙还牙”^[26]战略的参与者更不容易产生合作。由原始的合作/非合作组合发展产生的合作战略的可行性也随着 p 的增加而降低。（3）耦合相位振荡的小世界网络的同步几乎与在平均场模型^[2]中的一样容易，尽管边的数量少了几个量级。这个结果可能与所观测到的视觉皮层中被广泛分离的神经元的同步性^[27]相关，如此看来，大脑似乎也具有小世界体系结构。 [英文](#)

我们希望本文可以促进小世界网络更深层次的研究。小世界网络同时具有高聚集度与短特征路径长度的独特特征，不能用传统的近似方法例如基于规则晶格网络或者随机图的方法来获得。尽管小世界体系结构还没有引起很大的关注，我们推测它将在生物、社会以及人工系统等广泛存在，并且通常对系统的动力学行为有重要的影响。 [英文](#)

（崔宁 翻译；狄增如 审稿）

An Electrophoretic Ink for All-printed Reflective Electronic Displays

B. Comiskey *et al.*

The printed word retains some advantages over electronic displays. The subliminal flickering of screens tires the eye, and they are fragile, expensive, energy-hungry, and lose contrast in bright ambient light. This has stimulated a quest for “electronic paper” that combines the benefits of printed paper with the convenience and versatility of electronic information systems. Here researchers at MIT’s Media Lab report one of the first candidate materials: a layer of transparent microcapsules on a flexible plastic sheet. Each capsule contains white and black pigment particles that can be drawn to the top surface by an electric field. This foundational paper led to a spinoff company, E-Ink, which, in partnership with microelectronics companies, now sells a range of portable display devices. [中文](#)

It has for many years been an ambition of researchers in display media to create a flexible low-cost system that is the electronic analogue of paper. In this context, microparticle-based displays¹⁻⁵ have long intrigued researchers. Switchable contrast in such displays is achieved by the electromigration of highly scattering or absorbing microparticles (in the size range 0.1–5 μm), quite distinct

from the molecular-scale properties that govern the behaviour of the more familiar liquid-crystal displays⁶. Microparticle-based displays possess intrinsic bistability, exhibit extremely low power d.c. field addressing and have demonstrated high contrast and reflectivity. These features, combined with a near-lambertian viewing characteristic, result in an “ink on paper” look⁷. But such displays have to date suffered from short lifetimes and difficulty in manufacture. Here we report the synthesis of an electrophoretic ink based on the microencapsulation of an electrophoretic dispersion⁸. The use of a microencapsulated electrophoretic medium solves the lifetime issues and permits the fabrication of a bistable electronic display solely by means of printing. This system may satisfy the practical requirements of electronic paper. [中文](#)

PREVIOUS approaches to fabricating particle-based displays have been based on rotating bichromal spheres in glass cavities¹ or elastomeric slabs^{2,3}, and electrophoresis in glass cavities^{4,5}. The advantageous optical and electronic characteristics of microparticle displays, as compared to liquid-crystal displays, result from the ability to electrostatically migrate highly scattering pigments such as titanium dioxide ($n=2.7$), yielding a difference in optical index of refraction with the surrounding dielectric liquid of $\Delta n=1.3$ and black pigments with very high absorption and hiding power. This results in a very short scattering length ($\sim 1\text{ }\mu\text{m}$) and a correspondingly high reflectivity and contrast, similar to that of ink on paper. For comparison, typical index differences in a scattering-mode liquid crystal are less than $\Delta n=0.25$ (ref. 9). [中文](#)

Despite these favourable attributes, microparticle displays at present suffer from a number of shortcomings. These include, in the case of the bichromal sphere system, difficulty in obtaining complete rotation (and thus complete contrast) due to a fall-off in the dipole force close

to normal angles and difficulty of manufacture. In the case of electrophoretic systems, the shortcomings include reduced lifetime due to colloidal instability¹⁰. Finally, bistable display media of all types, to date, are not capable of being manufactured with simple processes such as printing. (Although recent results have been obtained in ink-jetting of electroluminescent doped polymer films for organic light-emitting structures¹¹, such emissive non-bistable displays do not meet a key criterion of “electronic paper”, namely the persistent display of information with zero power consumption.)

中文

To realize a printable bistable display system, we have synthesized an electrophoretic ink by microencapsulating droplets of an electrophoretic dispersion in individual microcapsules with diameters in the range of 30–300 μm . Figure 1a indicates schematically the operation of a system of microencapsulated differently coloured and charged microparticles, in which one or the other species of particles may be migrated towards the viewer by means of an externally applied electric field. Figure 1b shows cross-sectional photomicrographs of a single microcapsule addressed with positive and negative fields.

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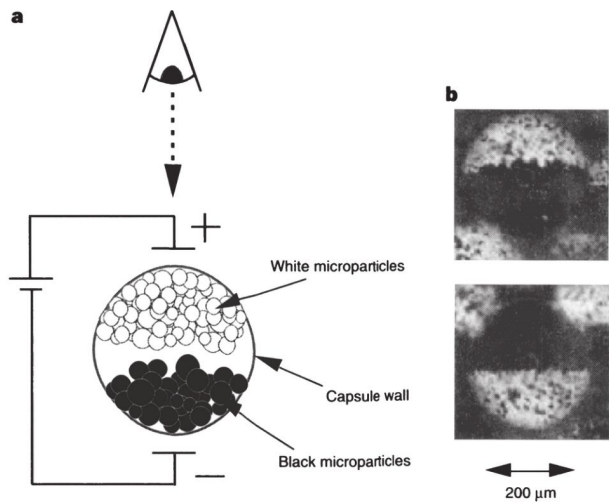


Fig. 1. Electrophoretic microcapsule. a, Schematic illustration of microencapsulated

electrophoretic image display (white and black microparticles system). The top transparent electrode becomes positively charged, resulting in negatively-charged white microparticles migrating towards it. Oppositely charged black microparticles move towards the bottom electrode. **b**, Photomicrograph of an individual microcapsule addressed with a positive and negative field. [中文](#)

The microencapsulated electrophoretic system was synthesized using the following process. The internal phase of the microcapsules was composed of a mixed dispersion of black and white microparticles in a dielectric fluid. To obtain white microparticles, a suspension of rutile titanium dioxide (specific gravity=4.2) in molten low-molecular-weight polyethylene was atomized. A similar process was used to prepare black microparticles with an inorganic black pigment. The resulting particles were sieved to obtain a dry powder with an average diameter of 5 μm . Alternatively, smaller monodisperse particles, with a diameter less than 1 μm , were prepared chemically. The polyethylene serves to reduce the specific gravity of the particles (typically to ~ 1.5) and present a modified surface chemistry for charging purposes. The particles in suspension acquire a surface charge due to the electrical double layer¹². The black and white particles have different zeta potential (and hence different mobility) due to the electroconductivity of the black pigment¹³. These microparticles are then dispersed in a mixture of tetrachloroethylene (specific gravity, 1.6) and an aliphatic hydrocarbon (specific gravity, 0.8) which is specific-gravity-matched to the manufactured particles. In the case where the particles are designed with charges of opposite sign, they are prevented from coagulation by providing a physical polymeric adsorbed layer on the surface of each particle which provides strong inter-particle repulsive forces¹⁰. Alternatively, a single particle system (white microparticles) dispersed in a dyed (Oil Blue N) dielectric fluid was prepared. [中文](#)

This suspension, which in typical electrophoretic displays would be interposed between two glass electrodes, was then emulsified into an aqueous phase and microencapsulated by means of an *in situ*

polycondensation of urea and formaldehyde. This process produces discrete mechanically strong and optically clear microcapsules. The microcapsules are optionally filtered to obtain a desired size range, and are subsequently washed and dried. 中文

Microcapsules (white particle in dye) were prepared and dispersed in a carrier (ultraviolet-curable urethane) and subsequently coated onto a transparent conductive film (indium tin oxide (ITO) on polyester). Rear electrodes printed from a silver-doped polymeric ink were then applied to the display layer. Figure 2 shows a series of microphotographs at different magnifications in which the letter “k” has been electronically addressed in the electronic ink. The sample shown was sieved to have a mean capsule size of $40 \pm 10 \mu\text{m}$ yielding a capsule resolution of ~ 600 dots per inch. By going to a system using structured top electrodes (or address lines as opposed to a continuous electrode), we were able to fractionally address single microcapsules, yielding an addressable resolution of $\sim 1,200$ dots per inch. 中文

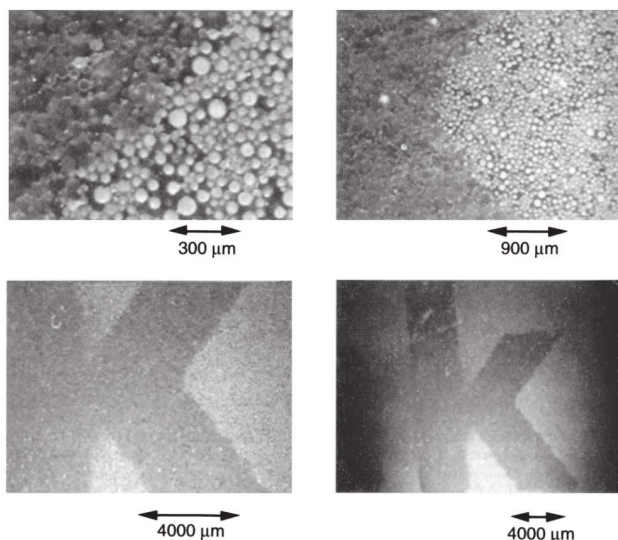


Fig. 2. Electrophoretic ink. Photomicrographs of 200- μm -thick film of electronic ink (“white particles in dye” type) with a capsule diameter of $40 \pm 10 \mu\text{m}$ (top view). The electronically addressed letter “k” is white, other areas are blue. 中文

In addition to making a flexible and printable system,

microencapsulating the electrophoretic dispersion has solved a longstanding problem with electrophoretic displays, namely limited lifetime due to particle clustering, agglomeration and lateral migration¹⁰. This is because the dispersion is physically contained in discrete compartments, and cannot move or agglomerate on a scale larger than the capsule size. In ink samples that we have prepared to date, $>10^7$ switching cycles have been observed with no degradation in performance. We have measured contrast ratios of 7:1 with 35% reflectance and a near-lambertian viewing characteristic. Using the same measurement system, we measured newspaper at 5:1 contrast and 55% reflectance. We have observed image storage times of several months, after which the material may be addressed readily. 中文

In Fig. 3a we show maximum minus minimum reflected optical power (non-normalized contrast) versus drive frequency for several different applied fields; open symbols indicate data taken from low to high frequency, filled symbols show data from high to low frequency. Figure 3b shows plots of contrast versus applied field for different frequencies. The data in Fig. 3 were obtained for a 200- μm film of electronic ink (of the type “white particles in dye”), with capsules of diameter $40 \pm 10 \mu\text{m}$ on ITO polyester with a silver-ink rear electrode.

中文

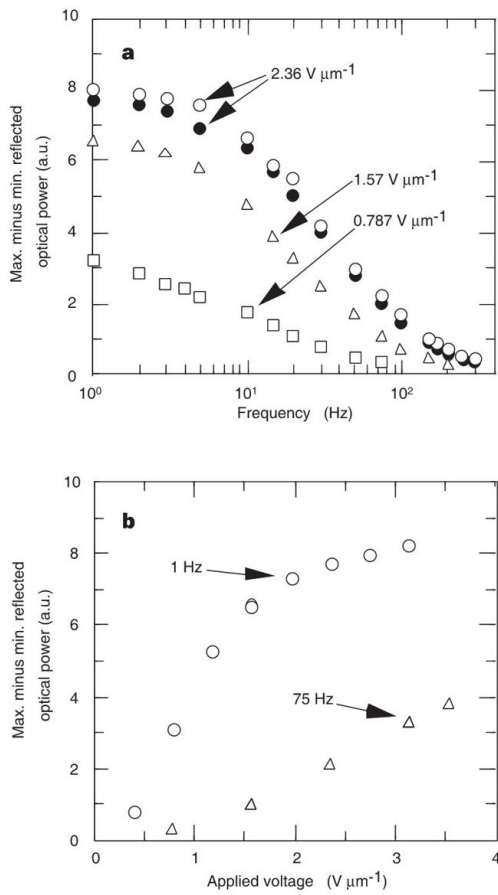


Fig. 3. Properties of a 200-μm-thick film of electronic ink (“white particles in dye” type) with capsule diameter of $40 \pm 10 \text{ } \mu\text{m}$. **a**, Maximum minus minimum reflected optical power (contrast) versus drive frequency for several different applied fields (open symbols, data taken from low to high frequency; filled symbols, from high to low frequency). **b**, Plot of contrast versus applied field for different frequencies. 中文

We may calculate the particle mobility, zeta potential and charge per particle as follows. The low-frequency asymptote in Fig. 3a indicates that at sufficiently slow driving frequency there is time for the internal particles to make a full traverse of the capsule, after which there is no further contribution to the contrast. Thus the cusp of the sigmoid in Fig. 3a may be taken to indicate the frequency (5 Hz) at which the particle just traverses a round trip ($2 \times 40 \text{ } \mu\text{m} = 80 \text{ } \mu\text{m}$) in the microcapsule yielding a velocity of $v = 400 \text{ } \mu\text{m s}^{-1}$. The Reynolds number is given by $\text{Re} = \rho v r \eta^{-1}$ where ρ is the internal fluid density,

r is the particle radius, η is the internal fluid viscosity and v is the particle velocity. For the present system we have $\rho = 1.6 \times 10^{-15} \text{ kg } \mu\text{m}^{-3}$, $v = 400 \text{ } \mu\text{m s}^{-1}$, $r = 0.5 \text{ } \mu\text{m}$, and $\eta = 0.8 \times 10^{-9} \text{ kg } \mu\text{m}^{-1} \text{ s}^{-1}$; and $\text{Re} = 0.0004 \ll 1$ and the flow is laminar¹⁴. The transient time to establish the laminar flow may be estimated from the Navier–Stokes equation to be $\tau_{ss} = (1 / 9)r^2 \rho \eta^{-1} = 55 \text{ ns}$. Thus for time-scales of interest, the particle mobility is given as $\mu = v / E = \epsilon \zeta / 6\pi\eta = q / 12\pi r \eta$ where ϵ is the dielectric constant of the internal fluid, ζ is the zeta potential of the particles and q is the charge per particle. Thus for our system we have $\mu = 169 \text{ } \mu\text{m}^2 \text{ V}^{-1} \text{ s}^{-1}$, $\epsilon = 2.5 \times 8.85 \times 10^{-6} \text{ kg } \mu\text{m s}^{-2} \text{ V}^{-2}$, $\zeta = 120 \text{ mV}$, and $q = 2.6 \times 10^{-18} \text{ C} = 16e^-$. The very small charge per particle indicates the mechanism for “field-off” bistability. Particle / capsule-wall and particle / particle binding dominate the particle / particle repulsion coming from the very small charge per particle. Other mechanisms for “field-off” bistability include charge redistribution and minimization. 中文

Figure 3a indicates the compromise between switching speed and contrast; Fig. 3b shows the compromise between applied field and contrast. In both sets of curves, the high-contrast asymptote indicates the regime in which the particles have made full traverse of the capsule, and further time or applied field has no further consequence. Two-particle (black / white particles) systems, as opposed to “single particle in dye” systems, relax these trade-offs due to the absence of exponential light absorption in the dye case due to dye interstitially present between white particles. 中文

In order to efficiently address a large number of pixels, matrix addressing is required. Matrix addressing in turn requires that either the contrast material (passive matrix) or an underlying electronic layer (active matrix) possess a threshold in order to prevent crosstalk between address lines. Typically, the display material may support passive matrix addressing for small numbers of pixels¹⁵. Larger

numbers of pixels require the nonlinearity of an electronic element as implemented in active matrix addressing¹⁶. Active matrix structures, typically formed from polysilicon on glass, are expensive and would obviate many of the advantages of a flexible low-cost paper-like display. Our group has recently demonstrated an all-printed metal-insulator-metal (MIM) diode structure¹⁷ capable of forming the active matrix for electrophoretic ink, which should enable us to drive high-pixel-count sheets of electrophoretic ink while maintaining the ease of fabrication and low-cost structure provided by the ink material itself. Work by other groups may also be of use in this endeavour¹⁸. We believe that such systems will open up a new field of research in printable microscopic electro-mechanical systems. Coupled with recent advances in printable logic, such technology offers the prospect of fundamentally changing the nature of printing, from printing form to printing function. 中文

(394, 253-255; 1998)

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Received 8 December 1997; accepted 18 May 1998.

References:

1. Pankove, J. I. *Color Reflection Type Display Panel* (Tech. Note No. 535, RCA Lab., Princeton, NJ, 1962).
2. Sheridan, N. K. & Berkovitz, M. A. The gyricon—a twisting ball display. *Proc. Soc. Information Display* **18**(3,4), 289-293 (1977).
3. Sheridan, N. K. *et al.* in *Proc. Int. Display Research Conf.* (ed. Jay Morreale) L82–L85 (Toronto, 1997).
4. Ota, I., Honishi, J. & Yoshiyama, M. Electrophoretic image display panel. *Proc. IEEE* **61**, 832-836 (1973).
5. Dalisa, A. L. Electrophoretic display technology. *IEEE Trans. Electron Devices* **ED-24**(7), 827-834 (1977).
6. Castellano, J. A. & Harrison, K. J. in *The Physics and Chemistry of Liquid Crystal Devices* (ed. Sprökel, G. J.) 263-288 (Plenum, New York, 1980).
7. Fitzhenry-Ritz, B. Optical properties of electrophoretic image displays. *IEEE Trans.*

8. Comiskey, B., Albert, J. D. & Jacobson, J. Electrophoretic ink: a printable display material. In *Digest of Tech. Papers* 75-76 (Soc. Information Display, Boston, 1997).
9. Okada, M., Hatano, T. & Hashimoto, K. Reflective multicolor display using cholesteric liquid crystals. In *Digest of Tech. Papers* 1019-1026 (Soc. Information Display, Boston, 1997).
10. Murau, P. & Singer, B. The understanding and elimination of some suspension instabilities in an electrophoretic display. *J. Appl. Phys.* **49**, 4820-4829 (1978).
11. Hebner, T. R., Wu, C. C., Marcy, D., Lu, M. H. & Sturm, J. C. Ink-jet printing of doped polymers for organic light emitting devices. *Appl. Phys. Lett.* **72**, 519-521 (1998).
12. Fowkes, F. M., Jinnai, H., Mostafa, M. A., Anderson, F. W. & Moore, R. J. in *Colloids and Surfaces in Reprographic Technology* (eds Hair, M. & Croucher, M. D.) (Am. Chem. Soc., Washington DC, 1982).
13. Claus, C. J. & Mayer, E. F. in *Xerography and Related Processes* (eds Dessauer, J. H. & Clark, H. E.) 341-373 (Focal, New York, 1965).
14. Landau, L. D. & Lifshitz, E. M. *Fluid Mechanics* (Pergamon, New York, 1959).
15. Ota, I., Sato, T., Tanka, S., Yamagami, T. & Takeda, H. Electrophoretic display devices. In *Laser* **75** 145-148 (Optoelectronics Conf. Proc., Munich, 1975).
16. Shiffman, R. R. & Parker, R. H. An electrophoretic image display with internal NMOS address logic and display drivers. *Proc. Soc. Information Display* **25.2**, 105-115 (1984).
17. Park, J. & Jacobson, J. in *Proc. Materials Research Soc.* B8.2 (Mater. Res. Soc., Warrendale, PA, 1998).
18. Service, R. F. Patterning electronics on the cheap. *Science* **278**, 383 (1997).

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一种可用于全印刷反射式电子显示器的电泳墨水

科米斯基等

与电子显示相比，印刷的文字仍然具有一定的优势。电子显示器的轻微闪烁容易使眼睛疲劳，另外，它们易碎、昂贵、耗能，在明亮的环境光线下对比度下降。因而刺激了能够兼顾纸质印刷物的优点和电子信息系统的便利性与广泛性的“电子纸张”的需求。麻省理工学院媒体实验室的研究人员在本文中报道了首选材料之一：置于软塑料片上的透明微胶囊层。每个胶囊中都含有在电场中可移向顶面的黑、白两种颜色的微粒。这篇基础性的文章导致一个派生公司——E-Ink的问世，该公司与微电子公司合作后，一系列便携式显示设备已进入市场。 [英文](#)

长期以来，显示媒介领域的研究人员一直有一种追求，即发明一种柔韧的低成本系统，也就是实现纸张的电子模拟。在这种情况下，基于微粒的显示器^[1-5]早已引起了研究人员们的兴趣。这类显示器中可切换的对比度是通过强散射或强吸收微粒（尺寸范围为 $0.1\sim 5\mu\text{m}$ ）的电迁移来实现的，完全不同于人们熟知的通过分子的性质来调控的液晶显示器^[6]。基于微粒的显示器拥有本征双稳态，表现出极低的直流电场编址，并且具有很高的对比度和反射率。这些特征，再加之近朗伯显示特性，就能产生“纸上墨迹”的视觉效果^[7]。但是这类显示器却存在着寿命短，制作难度大的缺点。本文中我们报道了一种基于电泳分散微胶囊化^[8]的电泳型墨水的合成。使用微胶囊化的电泳介质解决了寿命问题，并且实现了仅用印刷技术便可制造双稳态电子显示器的要求。该系统可以达到电子纸张应用于实际的要求。 [英文](#)

以往生产基于微粒的显示器的方法是以在玻璃腔^[1]或弹性板^[2,3]中的双色拧转球，和它们在玻璃腔中的电泳^[4,5]为基础的。与液晶显示器相比，微粒显示器具有优越的光学和电学特性，基于高散射颜料例如二氧化钛（ $n=2.7$ ）的静电迁移能力，使其和周围介电液体及高吸收和遮盖力黑色颜料之间的光学折射率差异较大（ $\Delta n=1.3$ ）。从而导致散射长度很短（约1 μm ）而相应的反射率和对比度很高，效果和纸上墨迹相近。相比较而言散射型液晶的典型折射率差值则小于 $\Delta n=0.25$ （参考文献9）。 [英文](#)

尽管具有这些有利的属性，现阶段的微粒显示器仍然存在许多缺点。其中包括，在双色拧转球系统中，由于在接近直角时偶极力下降，使其难以完全拧转（从而达到最大反差），此外还有制造上的困难。至于电泳系统，缺点包括胶体不稳定性^[10]引起的寿命缩短。总之，至今为止，各种类型的双稳态显示媒体都不可能通过如印刷这样的简单过程来生产。（尽管用喷墨法在掺杂的电致发光聚合物薄膜上制备有机发光结构最近已有进展^[11]，但这类发光非双稳态显示器并没有达到“电子纸张”的关键指标，即零能耗时信息的持久显示。） [英文](#)

为了实现可印刷的双稳态显示系统，我们合成了一种电泳墨水，通过将电泳分散的液滴微胶囊化，微胶囊的直径范围为30~300 μm 。图1a显示了不同颜色的带电微粒微胶囊化系统的操作示意图，在该系统中一种或另一种粒子可以通过外加电场移向观察者。图1b显示了用正负电场编址的单一微胶囊的横截面显微照片。 [英文](#)

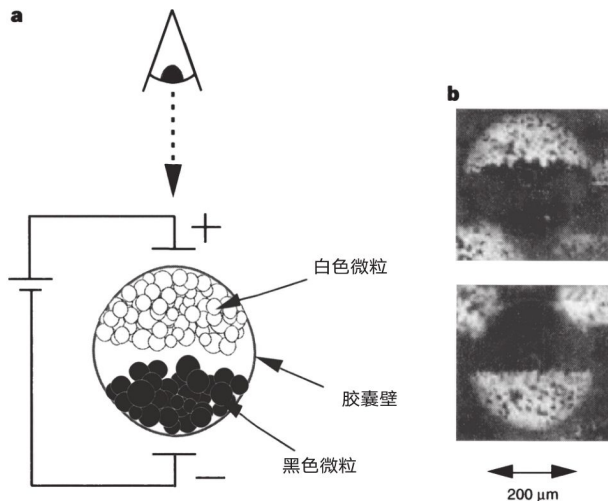


图1．电泳微胶囊。**a**，电泳成像显示器微胶囊化的示意图（黑白微粒系统）。上方的透明电极带正电，引起带负电的白色微粒向它迁移。带相反电荷的黑色微粒向下方电极迁移。**b**，用正电场编址单个微胶囊的显微照片。 [英文](#)

微胶囊电泳系统经由以下工序合成。微胶囊的分散相由黑白微粒在介电流体的分散系混合而成。白色微粒是通过金红石型二氧化钛（比重 $=4.2$ ）在熔化的低分子量聚乙烯的悬浮液中雾化而成。黑色微粒可用无机黑色颜料经过类似的过程制备。所得粒子经筛分得到平均直径为 $5\ \mu\text{m}$ 的干粉。此外直径小于 $1\ \mu\text{m}$ 的较小单分散粒子可用化学方法制备。聚乙烯用来降低粒子的比重（通常降至 1.5 左右）和提供经化学修饰的表面使之能够带电。悬浮液中粒子表面电荷来自双电层作用^[12]。黑色颜料的导电性使黑白粒子具有不同的界面电位（进而有不同的迁移率）^[13]。这些微粒被分散于四氯乙烯（比重 1.6 ）和一种脂肪烃（比重 0.8 ）的混合物中，混合物与所制备粒子的比重相匹配。在粒子按设计分别带有异性电荷的情况下，在粒子表面上通过物理吸附覆盖上一层高聚物，使得粒子间存在强互斥力^[10]以避免发生聚沉。此外，还制备了分散在染色（油蓝N）介电流体中的单粒子系统（白色微粒）。 [英文](#)

该悬浮液置于典型电泳显示器的两块玻璃电极之间，在水相中乳化并通过尿素和甲醛的原位缩聚反应实现微胶囊化。该方法可制得高强度、光学性能清晰、分立的微胶囊。筛选后可获得所需尺寸范围的微胶囊，随之进行清洗和干燥。 [英文](#)

在载体（紫外光固化的聚氨酯）中制备和分散微胶囊（染料中的白

色粒子)后,随即覆以透明导电薄膜(载有氧化铟锡(ITO)的聚酯)。然后,用于显示层的背电极由银掺杂的聚合物墨水印制而成。图2显示了不同放大率下的一系列显微照片,为字母“k”在电子墨水中的电子编址。所示样品曾经过筛选,胶囊平均尺寸为 $40 \pm 10 \mu\text{m}$,得到的胶囊分辨率为每英寸约600点。通过运用结构化的面电极(或者编址线与连续电极方向相反)系统,我们可对部分单一微胶囊编址,得到的编址分辨率为每英寸约1,200点。 英文

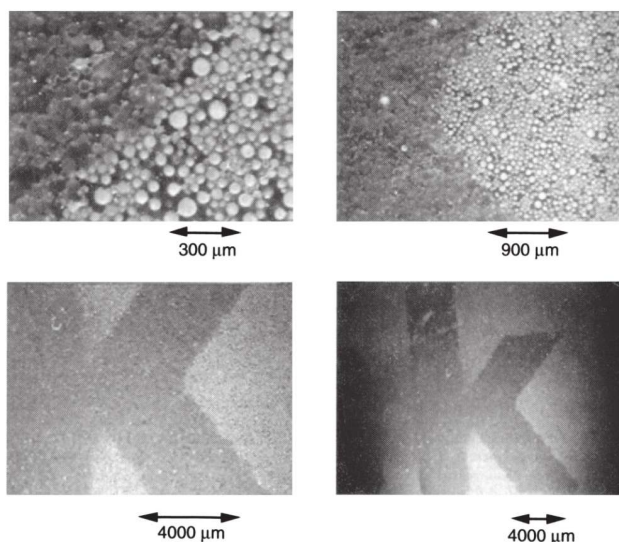


图2. 电泳墨水。胶囊直径为 $40 \pm 10 \mu\text{m}$,厚度为 $200 \mu\text{m}$ 的电子墨水(“染料中白色粒子”型)薄膜显微照片(俯视图)。电子编址的字母“k”为白色,其他区域为蓝色。 英文

除了制作灵活的可印刷系统之外,微胶囊电泳分散法解决了电泳显示器的一个存在已久的问题,即由于粒子簇集,聚沉,以及横向迁移带来的寿命受限问题^[10]。因为分散被物理地限制在分立的空间中,移动和聚集都不可能超出胶囊的尺寸。目前为止,我们制备的墨水样品,经 10^7 次以上的切换循环,没有观测到性能有所下降。测量得到的对比度为7:1,反射率为35%,并且观测到近朗伯显示特性。运用相同的测量系统,我们测得报纸的对比度为5:1,反射率为55%。而且经几个月的存放后,该材料仍然可以很容易地编址。 英文

图3a中展示了反射光强的最大和最小值之差(对比度未归一化)与不同外加场下驱动频率的关系;空心图形代表频率由低至高时采集的数据,实心图形代表频率由高至低时所采集的数据。图3b为不同频率下对

比度与外加电场的关系。图3中的数据源于200 μm 的电子墨水（“染料中白色粒子”型）薄膜，在具有银墨水背电极的ITO聚酯膜上的胶囊直径为 $40 \pm 10 \mu\text{m}$ 。英文

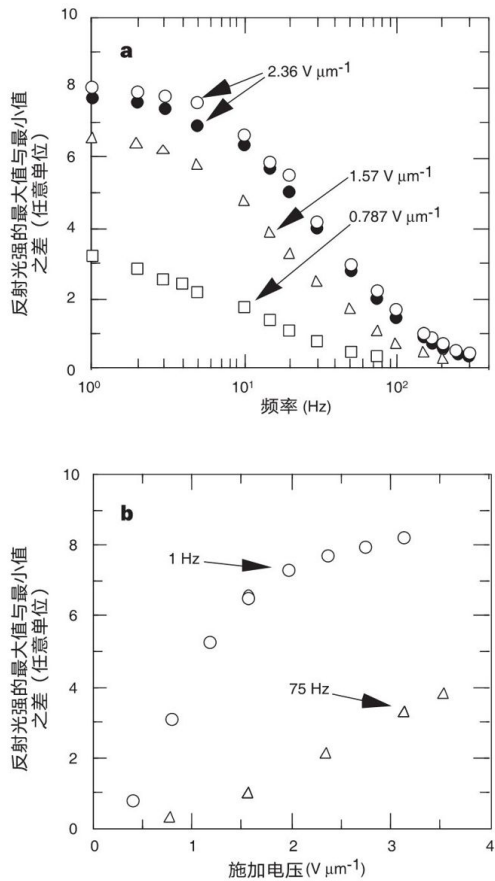


图3．胶囊直径为 $40 \pm 10 \mu\text{m}$ ，厚度为 $200 \mu\text{m}$ 的电子墨水（“染料中白色粒子”型）薄膜的属性。
a，反射光强的最大值与最小值之差（对比度）与不同外场下驱动频率的关系（空心图形，频率由低至高采集的数据；实心图形，频率由高至低所采集的数据）。b，不同频率下对比度与外场的关系。英文

我们可以通过如下方法计算粒子的迁移率、界面电位和单位粒子的荷电量。图3a中低频渐近线意味着当驱动频率足够低时，内部粒子有时间完全横穿胶囊，之后对对比度没有进一步的贡献。因此图3a中S形的突起点可以视为粒子刚好在胶囊中以5 Hz的频率往返一周（ $2 \times 40 \mu\text{m} = 80 \mu\text{m}$ ）时的速率，为 $v = 400 \mu\text{m} \cdot \text{s}^{-1}$ 。雷诺常数由 $\text{Re} = \rho v r \eta^{-1}$ 给出，其中 ρ 为内部流体密度， r 为粒子半径， η 为内部流体黏度， v 为粒子速度。对于现在的系统，有 $\rho = 1.6 \times 10^{-15} \text{ kg} \cdot \mu\text{m}^{-3}$ ， $v = 400 \mu\text{m} \cdot \text{s}^{-1}$

1 , $r=0.5\text{ }\mu\text{m}$, $\eta=0.8\times 10^{-9}\text{ kg}\cdot\mu\text{m}^{-1}\cdot\text{s}^{-1}$, $\text{Re}=0.0004\ll 1$, 并且流动为层流^[14]。确定层流的瞬态时间可以从纳维-斯托克斯方程中估算出来, 为 $\tau_{ss}=(1/9)r^2\rho\eta^{-1}=55\text{ ns}$ 。因此在我们所感兴趣的时间尺度之内, 粒子迁移率可以表示为 $\mu=v/E=e\zeta/6\pi\eta=q/12\pi r\eta$, 其中 e 为内部流体的介电常数, ζ 为粒子的界面电位, q 为单位粒子的电量。对于我们的系统, $\mu=169\text{ }\mu\text{m}^2\cdot\text{V}^{-1}\cdot\text{s}^{-1}$, $e=2.5\times 8.85\times 10^{-6}\text{ kg}\cdot\mu\text{m}\cdot\text{s}^{-2}\cdot\text{V}^{-2}$, $\zeta=120\text{ mV}$, $q=2.6\times 10^{-18}\text{ C}=16e^{-}$ 。单位粒子带电量极低表示遵守“去场”双稳态机制。粒子/胶囊壁和粒子/粒子间的结合对来自带电量很小的微粒间的粒子/粒子互斥起主导作用。“去场”双稳态的其他机制包括电荷再分布以及最小化。 英文

图3a指示出切换速度与对比度之间的制约关系; 图3b显示了外场与对比度之间的制约关系。在两组曲线中, 高对比度渐近线暗示着粒子完全穿越胶囊的机制, 随后时间和外场都不再起作用。和“染料中的单粒子系统”不同的是, 在双粒子(黑/白粒子)系统中, 由于白粒子处于染料之中, 而染料对光不发生指数型吸收, 因而削弱了这种制约。 英文

大量像素的有效编址要应用矩阵编址。矩阵编址又依次要求对比材料(被动矩阵)或者基本电层(主动矩阵)具有一个阈值以防止编址线之间的串扰。通常, 显示材料可以支持少量像素的被动矩阵编址^[15]。大量像素要求电子元件在实现主动矩阵编址时具有非线性^[16]。主动矩阵结构, 通常是由在玻璃上的多晶硅形成, 昂贵而且不具备低成本的柔韧性类纸张显示器的许多优点。我们的团队近期提出了一种可印刷的金属-绝缘体-金属(MIM)的二极管结构^[17], 可以组成电泳墨水的主动矩阵, 应当有可能使驱动电泳墨水的高像素数印刷板成为现实, 因为使用了这种墨水材料, 保持了制造的简单易行和结构的低成本。其他团队的工作也可能应用到这项研究之中^[18]。我们相信这种系统会开创可印刷微观机电系统的一个新研究领域。结合现阶段其他可印刷技术的思路, 这种技术预期将从根本上改变印刷的特性, 从印刷形式到印刷功能。 英文

(崔宁 翻译; 宋心琦 审稿)

Light Speed Reduction to 17 Metres per Second in an Ultracold Atomic Gas

L. V. Hau *et al.*

Light moves more slowly in physical media than in empty space—but generally only by a little. Yet interference effects associated with quantum physics can in principle be used to slow the speed of light dramatically in a specially designed medium. Here, Lene Vestergaard Hau and colleagues demonstrate this effect in an ultracold gas of sodium atoms. They use a laser beam travelling at right angles to a test beam to prepare the atoms such that a fraction of them are in particular excited electronic states. Light in the test beam, being repeatedly absorbed and re-emitted by these atoms, travels at a speed of only 17 metres per second, some 20 million times slower than light in a vacuum. [中文](#)

Techniques that use quantum interference effects are being actively investigated to manipulate the optical properties of quantum systems¹. One such example is electromagnetically induced transparency, a quantum effect that permits the propagation of light pulses through an otherwise opaque medium²⁻⁵. Here we report an experimental demonstration of electromagnetically induced transparency in an ultracold gas of sodium atoms, in which the optical pulses propagate at twenty million times slower than the

speed of light in a vacuum. The gas is cooled to nanokelvin temperatures by laser and evaporative cooling⁶⁻¹⁰. The quantum interference controlling the optical properties of the medium is set up by a “coupling” laser beam propagating at a right angle to the pulsed “probe” beam. At nanokelvin temperatures, the variation of refractive index with probe frequency can be made very steep. In conjunction with the high atomic density, this results in the exceptionally low light speeds observed. By cooling the cloud below the transition temperature for Bose–Einstein condensation¹¹⁻¹³ (causing a macroscopic population of alkali atoms in the quantum ground state of the confining potential), we observe even lower pulse propagation velocities (17 m s^{-1}) owing to the increased atom density. We report an inferred nonlinear refractive index of $0.18 \text{ cm}^2 \text{ W}^{-1}$ and find that the system shows exceptionally large optical nonlinearities, which are of potential fundamental and technological interest for quantum optics. [中文](#)

THE experiment is performed with a gas of sodium atoms cooled to nanokelvin temperatures. Our atom cooling set-up is described in some detail in ref. 14. Atoms emitted from a “candlestick” atomic beam source¹⁵ are decelerated in a Zeeman slower and loaded into a magneto-optical trap. In a few seconds we collect a cloud of 10^{10} atoms at a temperature of 1 mK and a density of $6 \times 10^{11} \text{ cm}^{-3}$. The atoms are then polarization gradient cooled for a few milliseconds to 50 μK and optically pumped into the $F=1$ ground state with an equal population of the three magnetic sublevels. We then turn all laser beams off and confine the atoms magnetically in the “4 Dee” trap¹⁴. Only atoms in the $M_F = -1$ state, with magnetic dipole moments directed opposite to the magnetic field direction (picked as the quantization axis), are trapped in the asymmetric harmonic trapping potential. This magnetic filtering results in a sample of atoms that are all in a single atomic state (state $|1\rangle$ in Fig. 1b) which allows

adiabatic optical preparation of the atoms, as described below, and minimal heating of the cloud. [中文](#)

Next we evaporatively cool the atoms for 38 s to the transition temperature for Bose–Einstein condensation, T_c . The magnetic fields are then adjusted to adiabatically soften the trap. The resulting trapping potential has a frequency of $f_z = 21$ Hz along the symmetry (z) axis of the 4 Dee trap, and transverse frequencies $f_x = f_y = 69$ Hz. The bias field, parallel to the z axis, is 11 G. When we cool well below T_c , we are left with 1–2 million atoms in the condensate. For these parameters the transition occurs at a temperature of $T_c = 435$ nK and a peak density in the cloud of $5 \times 10^{12} \text{ cm}^{-3}$. [中文](#)

We now apply a linearly polarized laser beam, the coupling beam, tuned to the transition between the unpopulated hyperfine states $|2\rangle$ and $|3\rangle$ (Fig. 1b). This beam couples states $|2\rangle$ and $|3\rangle$ and creates a quantum interference for a weaker probe laser beam (left circularly polarized) which is tuned to the $|1\rangle \rightarrow |3\rangle$ transition. A stable eigenstate (the “dark state”) of the atom in the presence of coupling and probe lasers is a coherent superposition of the two hyperfine ground states $|1\rangle$ and $|2\rangle$. The ratio of the probability amplitudes is such that the contributions to the atomic dipole moment induced by the two lasers exactly cancel. The quantum interference occurs in a narrow interval of probe frequencies, with a width determined by the coupling laser power. [中文](#)

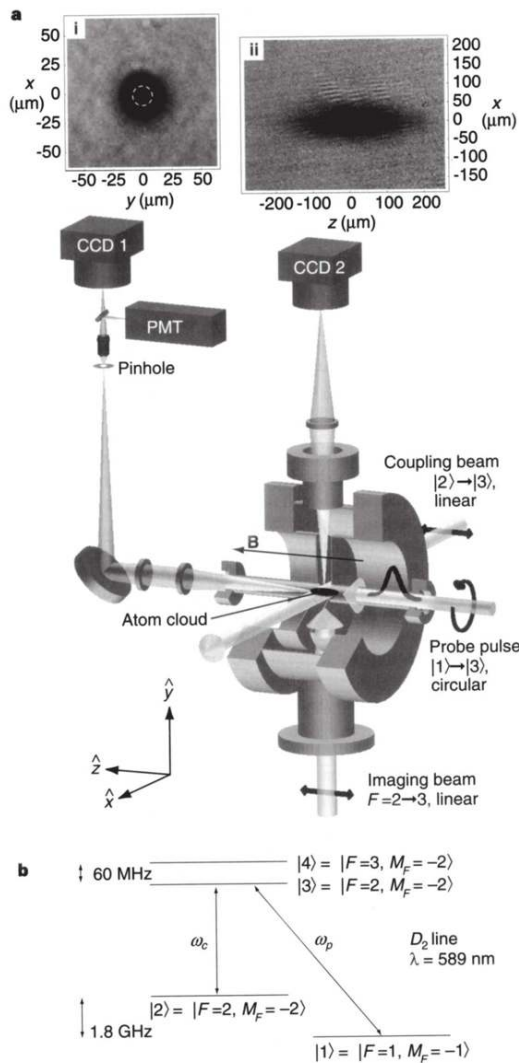


Fig. 1. Experimental set-up. A “coupling” laser beam propagates along the x axis with its linear polarization along the 11-G bias field in the z direction. The “probe” laser pulse propagates along the z axis and is left-circularly polarized. With a flipper mirror in front of the camera CCD 1, we direct this probe beam either to the camera or to the photomultiplier (PMT). For pulse delay measurements, we place a pinhole in an external image plane of the imaging optics and select a small area, 15 μm in diameter, of the probe beam centred on the atom clouds (as indicated by the dashed circle in inset (i)). The pulse delays are measured with the PMT. The imaging beam propagating along the y axis is used to image atom clouds onto camera CCD 2 to find the length of the clouds along the pulse propagation direction (z axis) for determination of light speeds. Inset (ii) shows atoms cooled to 450 nK which is 15 nK above T_c . (Note that this imaging beam is never applied at the same time as the probe pulse and coupling laser). The position of a cloud and its diameter in the two transverse directions, x and y , are found with CCD 1. Inset (i) shows an image of a condensate. 中文

Figure 2a shows the calculated transmission of the probe beam as a function of its detuning from resonance for parameters which are typical of this work. In the absence of dephasing of the $|1\rangle \rightarrow |2\rangle$ transition, the quantum interference would be perfect, and at line centre, the transmission would be unity. Figure 2b shows the refractive index for the probe beam as a function of detuning. Due to the very small Doppler broadening of the $|1\rangle \rightarrow |2\rangle$ transition in our nanokelvin samples, application of very low coupling intensity leads to a transparency peak with a width much smaller than the natural line width of the $|1\rangle \rightarrow |3\rangle$ transition. Correspondingly, the dispersion curve is much steeper than can be obtained by any other technique, and this results in the unprecedented low group velocities reported here. The group velocity v_g for a propagating electromagnetic pulse is¹⁶⁻¹⁹:

$$v_g = \frac{c}{n(\omega_p) + \omega_p \frac{dn}{d\omega_p}} \approx \frac{\hbar c \epsilon_0}{2\omega_p} \frac{|\Omega_c|^2}{|\mu_{13}|^2 N} \quad (1)$$

Here $n(\omega_p)$ is the refractive index at probe frequency ω_p (rad s^{-1}), $|\Omega_c|^2$ is the square of the Rabi frequency for the coupling laser and varies linearly with intensity, μ_{13} is the electric dipole matrix element between states $|1\rangle$ and $|3\rangle$, N is the atomic density, and ϵ_0 is the permittivity of free space. At line centre, the refractive index is unity, and the second term in the denominator of equation (1) dominates the first. An important characteristic of the refractive index profile is that on resonance the dispersion of the group velocity is zero (see ref. 16), that is, $d^2n/d\omega_p^2 = 0$, and to lowest order, the pulse maintains its shape as it propagates. The established quantum interference allows pulse transmission through our atom clouds which would otherwise have transmission coefficients of e^{-110} (below T_c), and creates a steep dispersive profile and very low group velocity for light pulses propagating through the clouds. 中文

We note that the centres of the curves in Fig. 2 are shifted by 0.6 MHz from probe resonance. This is due to a coupling of state $|2\rangle$ to state $|4\rangle$ through the coupling laser field, which results in an a.c. Stark shift of level $|2\rangle$ and a corresponding line shift of the $2\rightarrow 3$ transition. As the transparency peak and unity refractive index are obtained at two-photon resonance, this leads to a refractive index at the $1\rightarrow 3$ resonance frequency which is different from unity. The difference is proportional to the a.c. Stark shift and hence to the coupling laser intensity, which is important for predicting the nonlinear refractive index as described below. [中文](#)

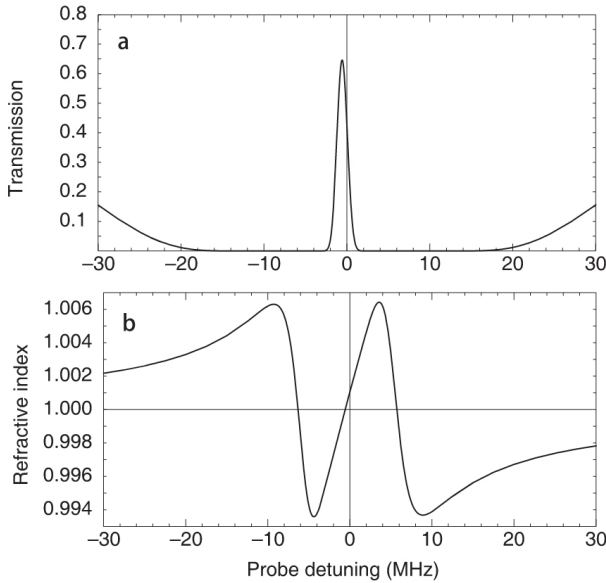


Fig. 2. Effect of probe detuning. **a**, Transmission profile. Calculated probe transmission as a function of detuning from the $|1\rangle\rightarrow|3\rangle$ resonance for an atom cloud cooled to 450 nK, with a peak density of $3.3 \times 10^{12} \text{ cm}^{-3}$ and a length of 229 μm (corresponding to the cloud in inset (ii) of Fig. 1a). The coupling laser is resonant with the $|2\rangle\rightarrow|3\rangle$ transition and has a power density of 52 mW cm^{-2} . **b**, Refractive index profile. The calculated refractive index is shown as a function of probe detuning for the same parameters as in **a**. The steepness of the slope at resonance is inversely proportional to the group velocity of transmitted light pulses and is controlled by the coupling laser intensity. Note that as a result of the a.c. Stark shift of the $|2\rangle\rightarrow|3\rangle$ transition, caused by a coupling of states $|2\rangle$ and $|4\rangle$ through the coupling laser field, the centre of the transmission and refractive index profiles is shifted by 0.6 MHz. The shift of the refractive index profile results in the nonlinear refractive index described in the text.

A diagram of the experiment is shown in Fig. 1a. The 2.5-mm-diameter coupling beam propagates along the x axis with its linear polarization parallel to the $\mathbf{B}$ field. The 0.5-mm-diameter, σ^- -polarized probe beam propagates along the z axis. The size and position of the atom cloud in the transverse directions, x and y , are obtained by imaging the transmission profile of the probe beam after the cloud onto a charge-coupled-device (CCD) camera. An image of a condensate is shown as inset (i). A 55 mW cm^{-2} coupling laser beam was present during the $10\text{-}\mu\text{s}$ exposure of the atoms to a 5 mW cm^{-2} probe beam tuned close to resonance. The $f/7$ imaging optics are diffraction-limited to a resolution of $7 \mu\text{m}$. 中文

During the pulse delay experiments, a pinhole (placed in an external image plane of the lens system) is used to select only the part of the probe light that has passed through the central $15 \mu\text{m}$ of the atom cloud where the column density is the greatest. The outline of the pinhole is indicated with the dashed circle in inset (i). 中文

Both coupling and probe beams are derived from the same dye laser. The frequency of the coupling beam is set by an acousto-optic modulator (AOM) to the $|2\rangle \rightarrow |3\rangle$ resonance. Here we take into account both Zeeman shifts and the a.c. Stark shift described above.

中文

The corresponding probe resonance is found by measuring the transmission of the probe beam as a function of its frequency. We apply a fast frequency sweep, across 32 MHz in $50 \mu\text{s}$, and determine resonance from the transmission peak. The sweep is controlled by a separate AOM. The frequency is then fixed at resonance, and the temporal shape of the probe pulse is generated by controlling the r.f. drive power to the AOM. The resulting pulse is approximately gaussian with a full-width at half-maximum of $2.5 \mu\text{s}$. The peak power is 1 mW cm^{-2} corresponding to a Rabi frequency of $\Omega_p = 0.20 A$, where the Einstein A coefficient is $6.3 \times 10^7 \text{ rad s}^{-1}$. To avoid

distortion of the pulse, it is made of sufficient duration that its Fourier components are contained within the transparency peak. [中文](#)

Probe pulses are launched along the z axis $4\text{ }\mu\text{s}$ after the coupling beam is turned on (the coupling field is left on for $100\text{ }\mu\text{s}$). Due to the magnetic filtering discussed above, all atoms are initially in state $|1\rangle$ which is a dark state in the presence of the coupling laser only. When the pulse arrives, the atoms adiabatically evolve so that the probability amplitude of state $|2\rangle$ is equal to the ratio $\Omega_p/(\Omega_p^2 + \Omega_c^2)^{1/2}$, where Ω_p is the probe Rabi frequency. To establish the coherent superposition state, energy is transferred from the front of the probe pulse to the atoms and the coupling laser field. At the end of the pulse, the atoms adiabatically return to the original state $|1\rangle$ and the energy returns to the back of the probe pulse with no net energy and momentum transfer to the atomic cloud. Because the refractive index is unity, the electric field is unchanged as the probe pulse enters the medium. As the group velocity is decreased, the total energy density must increase so as to keep constant the power per area. This increase is represented by the energy stored in the atoms and the coupling laser field during pulse propagation through the cloud. [中文](#)

The pulses are recorded with a photomultiplier (3-ns response time) after they penetrate the atom clouds. The output from the photomultiplier is amplified by a 150-MHz-bandwidth amplifier and the waveforms are recorded on a digital scope. With a “flipper” mirror in front of the camera we control whether the probe beam is directed to the camera or to the photomultiplier. [中文](#)

The result of a pulse delay measurement is shown in Fig. 3. The front pulse is a reference pulse obtained with no atoms present. The pulse delayed by $7.05\text{ }\mu\text{s}$ was slowed down in an atom cloud with a length of $229\text{ }\mu\text{m}$ (see Fig. 1a, inset (ii)). The resulting light speed is 32.5 m s^{-1} . We used a coupling laser intensity of 12 mW cm^{-2} corresponding

to a Rabi frequency of $\Omega_c=0.56$ A. The cloud was cooled to 450 nK (which is 15 nK above T_c), the peak density was $3.3 \times 10^{12} \text{ cm}^{-3}$, and the total number of atoms was 3.8×10^6 . From these numbers we calculate that the pulse transmission coefficient would be e^{-63} in the absence of the coupling laser. The probe pulse was indeed observed to be totally absorbed by the atoms when the coupling beam was left off. Inhomogeneous broadening due to spatially varying Zeeman shifts is negligible (~ 20 kHz) for the low temperatures and correspondingly small cloud sizes used here. 中文

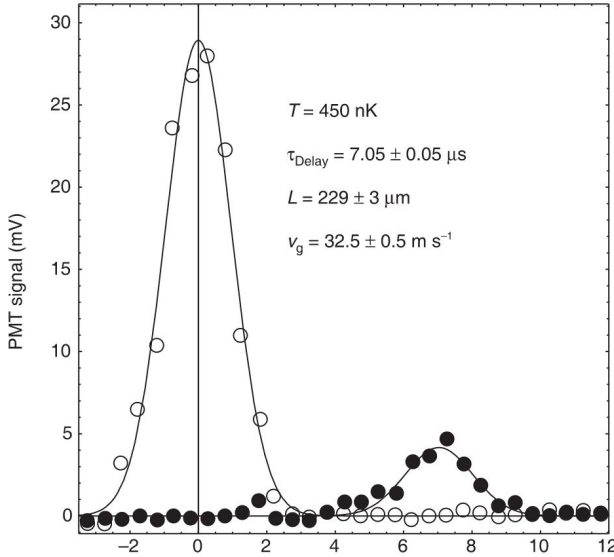


Fig. 3. Pulse delay measurement. The front pulse (open circles) is a reference pulse with no atoms in the system. The other pulse (filled circles) is delayed by $7.05 \mu\text{s}$ in a $229\text{-}\mu\text{m}$ -long atom cloud (see inset (ii) in Fig. 1a). The corresponding light speed is 32.5 m s^{-1} . The curves represent gaussian fits to the measured pulses. 中文

The size of the atom cloud in the z direction is obtained with another CCD camera. For this purpose, we use a separate 1 mW cm^{-2} laser beam propagating along the vertical y axis and tuned 20 MHz below the $F=2 \rightarrow 3$ transition. The atoms are pumped to the $F=2$ ground state for $10 \mu\text{s}$ before the imaging which is performed with an exposure time of $10 \mu\text{s}$. We image the transmission profile of the laser beam after the atom cloud with diffraction-limited $f/5$ optics. An example is shown in Fig. 1a, inset (ii), where the asymmetry of the

trap is clear from the cloud's elliptical profile. We note that the imaging laser is never applied at the same time as the coupling laser and probe pulse, and for each recorded pulse or CCD picture a new cloud is loaded. [中文](#)

We measured a series of pulse delays and corresponding cloud sizes for atoms cooled to temperatures between 2.5 μK and 50 nK. From these pairs of numbers we obtain the corresponding propagation velocities (Fig. 4). The open circles are for a coupling power of 52 mW cm^{-2} ($\Omega_c = 1.2 A$). The light speed is inversely proportional to the atom density (equation (1)) which increases with lower temperatures, with an additional density increase when a condensate is formed. The filled circles are for a coupling power of 12 mW cm^{-2} . The lower coupling power is seen to cause a decrease of group velocities in agreement with equation (1). We obtain a light speed of 17 m s^{-1} for pulse propagation in an atom cloud initially prepared as an almost pure Bose–Einstein condensate (condensate fraction is $\geq 90\%$). Whether the cloud remains a condensate during and after pulse propagation is an issue that is beyond the scope of this Letter. [中文](#)

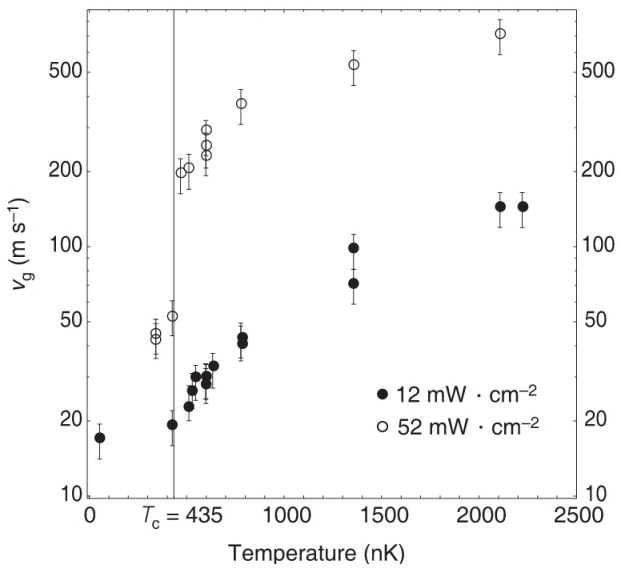


Fig. 4. Light speed versus atom cloud temperature. The speed decreases with temperature due

to the atom density increase. The open circles are for a coupling power of 52 mW cm^{-2} and the filled circles are for a coupling power of 12 mW cm^{-2} . The temperature T_c marks the transition temperature for Bose-Einstein condensation. The decrease in group velocity below T_c is due to a density increase of the atom cloud when the condensate is formed. From imaging measurements we obtain a maximum atom density of $8 \times 10^{13} \text{ cm}^{-3}$ at a temperature of 200 nK. Here, the dense condensate component constitutes 60% of all atoms, and the total atom density is 16 times larger than the density of a non-condensed cloud at T_c . The light speed measurement at 50 nK is for a cloud with a condensate fraction $\geq 90\%$. The finite dephasing rate due to state $|4\rangle$ does not allow pulse penetration of the most dense clouds. This problem could be overcome by tuning the laser to the D_1 line as described in the text. [中文](#)

Transitions from state $|2\rangle$ to state $|4\rangle$, induced by the coupling laser (detuned by 60 MHz from this transition), result in a finite decay rate of the established coherence between states $|1\rangle$ and $|2\rangle$ and limit pulse transmission. The dephasing rate is proportional to the power density of the coupling laser and we expect, and find, that probe pulses have a peak transmission that is independent of coupling intensity and a velocity which reduces linearly with this intensity. The dephasing time is determined from the slope of a semi-log plot of transmission versus pulse delay¹⁹. At a coupling power of 12 mW cm^{-2} , we measured a dephasing time of $9 \text{ }\mu\text{s}$ for atom clouds just above T_c . [中文](#)

Giant Kerr nonlinearities are of interest for areas of quantum optics such as optical squeezing, quantum nondemolition, and studies of nonlocality. It was recently proposed that they may be obtained using electromagnetically induced transparency²⁰. Here we report the first (to our knowledge) measurement of such a nonlinearity. The refractive index for zero probe detuning is given by $n=1 + (n_2 I_c)$ where I_c is the coupling laser intensity, and n_2 the cross phase nonlinear refractive index. As seen from Fig. 2b, the nonlinear term ($n_2 I_c$) equals the product of the slope of the refractive index at probe resonance and the a.c. Stark shift of the $|2\rangle \rightarrow |3\rangle$ transition caused by the coupling laser. We can then express n_2 by the formula (see equation (1));

$$n_2 = \frac{\Delta\omega_s}{I_c} \frac{dn}{d\omega_p} \approx \frac{1}{2\pi} \frac{\Delta\omega_s}{I_c} \frac{\lambda}{v_g} \quad (2)$$

where $\Delta\omega_s$ is the a.c. Stark shift, proportional to I_c , and λ the wavelength of the probe transition. We measured an a.c. Stark shift of $1.3 \times 10^6 \text{ rad s}^{-1}$ for a coupling laser intensity of 40 mW cm^{-2} . For a measured group velocity of 17 m s^{-1} (Fig. 4), we obtain a nonlinear refractive index of $0.18 \text{ cm}^2 \text{ W}^{-1}$. This nonlinear index is $\sim 10^6$ times greater than that measured in cold Cs atoms²¹. 中文

With a system that avoids the $|1\rangle - |2\rangle$ dephasing rate described above (which can be obtained by tuning to the D_1 line in sodium), the method used here could be developed to yield the collision-induced dephasing rate of the double condensate which is generated in the process of establishing electromagnetically induced transparency (see also refs 22, 23). In that case, the square of the probability amplitude for state $|3\rangle$ could be kept below 10^{-5} during pulse propagation, with no heating of the condensate as a result. With improved frequency stability of our set-up and lower coupling intensities, even lower light speeds would be possible, perhaps of the order of centimetres per second, comparable to the speed of sound in a Bose–Einstein condensate. Under these conditions we expect phonon excitation during light pulse propagation through the condensate. By deliberately tuning another laser beam to the $|2\rangle \rightarrow |4\rangle$ transition, it should be possible to demonstrate optical switching at the single photon level²⁴. Finally, we note that during propagation of the atom clouds, light pulses are compressed in the z direction by a ratio of c/v_g . For our experimental parameters, that results in pulses with a spatial extent of only $43 \mu\text{m}$. 中文

(397, 594-598; 1999)

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Received 3 November; accepted 21 December 1998.

References:

1. Knight, P. L., Stoicheff, B. & Walls, D. (eds) Highlights in quantum optics. *Phil. Trans. R. Soc. Lond. A* **355**, 2215-2416 (1997).
2. Harris, S. E. Electromagnetically induced transparency. *Phys. Today* **50(7)**, 36-42 (1997).
3. Scully, M. O. & Zubairy, M. S. *Quantum Optics* (Cambridge Univ. Press, 1997).
4. Arimondo, E. in *Progress in Optics* (ed. Wolf, E.) 257-354 (Elsevier Science, Amsterdam, 1996).
5. Bergmann, K., Theuer, H. & Shore, B. W. Coherent population transfer among quantum states of atoms and molecules. *Rev. Mod. Phys.* **70**, 1003-1006 (1998).
6. Chu, S. The manipulation of neutral particles. *Rev. Mod. Phys.* **70**, 685-706 (1998).
7. Cohen-Tannoudji, C. N. Manipulating atoms with photons. *Rev. Mod. Phys.* **70**, 707-719 (1998).
8. Phillips, W. D. Laser cooling and trapping of neutral atoms. *Rev. Mod. Phys.* **70**, 721-741 (1998).
9. Hess, H. F. Evaporative cooling of magnetically trapped and compressed spin-polarized hydrogen. *Phys. Rev. B* **34**, 3476-3479 (1986).
10. Masuhara, N. *et al.* Evaporative cooling of spin-polarized atomic hydrogen. *Phys. Rev. Lett.* **61**, 935-938 (1988).
11. Anderson, M. H., Ensher, J. R., Matthews, M. R., Wieman, C. E. & Cornell, E. A. Observation of Bose-Einstein condensation in a dilute atomic vapor. *Science* **269**, 198-201 (1995).
12. Davis, K. B. *et al.* Bose-Einstein condensation in a gas of sodium atoms. *Phys. Rev. Lett.* **75**, 3969-3973 (1995).
13. Bradley, C. C., Sackett, C. A. & Hulet, R. G. Bose-Einstein condensation of lithium: observation of limited condensate number. *Phys. Rev. Lett.* **78**, 985-989 (1997).
14. Hau, L. V. *et al.* Near-resonant spatial images of confined Bose-Einstein condensates in a 4-Dee magnetic bottle. *Phys. Rev. A* **58**, R54-R57 (1998).
15. Hau, L. V., Golovchenko, J. A. & Burns, M. M. A new atomic beam source: The "candlestick". *Rev. Sci. Instrum.* **65**, 3746-3750 (1994).
16. Harris, S. E., Field, J. E. & Kasapi, A. Dispersive properties of electromagnetically induced transparency. *Phys. Rev. A* **46**, R29-R32 (1992).
17. Grobe, R., Hioe, F. T. & Eberly, J. H. Formation of shape-preserving pulses in a nonlinear adiabatically integrable system. *Phys. Rev. Lett.* **73**, 3183-3186 (1994).
18. Xiao, M., Li, Y.-Q., Jin, S.-Z. & Gea-Banacloche, J. Measurement of dispersive properties of electromagnetically induced transparency in rubidium atoms. *Phys. Rev. Lett.* **74**, 666-669 (1995).
19. Kasapi, A., Jain, M., Yin, G. Y. & Harris, S. E. Electromagnetically induced transparency: propagation dynamics. *Phys. Rev. Lett.* **74**, 2447-2450 (1995).

20. Schmidt, H. & Imamoglu, A. Giant Kerr nonlinearities obtained by electromagnetically induced transparency. *Opt. Lett.* **21**, 1936-1938 (1996).
21. Lambrecht, A., Courty, J. M., Reynaud, S. & Giacobino, E. Cold atoms: A new medium for quantum optics. *Appl. Phys. B* **60**, 129-134 (1995).
22. Hall, D. S., Matthews, M. R., Wieman, C. E. & Cornell, E. A. Measurements of relative phase in two-component Bose-Einstein condensates. *Phys. Rev. Lett.* **81**, 1543-1546 (1998).
23. Ruostekoski, J. & Walls, D. F. Coherent population trapping of Bose-Einstein condensates: detection of phase diffusion. *Eur. Phys. J. D* (submitted).
24. Harris, S. E. & Yamamoto, Y. Photon switching by quantum interference. *Phys. Rev. Lett.* **81**, 3611-3614 (1998).

Acknowledgements. We thank J. A. Golovchenko for discussions and C. Liu for experimental assistance. L.V.H. acknowledges support from the Rowland Institute for Science. S.E.H. is supported by the US Air Force Office of Scientific Research, the US Army Research Office, and the US Office of Naval Research. C.H.B. is supported by an NSF fellowship.

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光速在超冷原子气中降低至17米每秒

豪等

光在物质媒介中的传播速度比在真空中的慢，但通常只慢一点点。然而，与量子物理相关的干涉效应原则上可以使光速在特别设计的介质中显著变慢。本文中，莱娜·韦斯特戈·豪和其同事们在超冷钠原子气体中展示了这种效应：使用与测试光束成直角传播的激光束来制备原子，使得其中的一部分处在特定的电子激发态。测试光束中的光，被这些原子反复吸收和重新发射，以每秒17米的速度传播，大约为真空中光速的2,000万分之一。 [英文](#)

基于量子干涉效应的技术被积极研究用来操纵量子系统中的光学性质^[1]。其中的一个例子就是电磁感应透明，一种允许光脉冲在其他状况下不透明的介质中传播的量子现象^[2-5]。在此，我们报道了在超冷钠原子气中电磁感应透明的实验验证，光脉冲以在真空中光速的2,000万分之一的速度在该介质中传播。气体通过激光和蒸发制冷被降温至纳开 (10^{-9} K) ^[6-10]。控制介质光学性质的量子干涉通过与脉冲“探测”光束成直角传播的“耦合”激光束来建立。在纳开温度下，折射率随探测频率可以发生非常急剧的变化。与高原子密度相结合，就会导致所观察到的极低光速。我们将原子云冷却至玻色-爱因斯坦凝聚临界温度^[11-13]以下（引起处于囚禁势量子基态的碱金属原子的宏观布居），由于原子数密度增大，我们观测到更低的脉冲传播速度 ($17 \text{ m}\cdot\text{s}^{-1}$)。经过测算，本文报道了该体系的非线性折射率系数为 $0.18 \text{ cm}^2\cdot\text{W}^{-1}$ ，发现该系统显示出非常大的光学非线性，这对于量子光学而言具有潜在的基础和技术吸引力。 [英文](#)

本实验是在降温至纳开的钠原子中进行的。文献14中对我们的原子冷却装置有一些细节性的描述。从“烛台”原子束源^[15]发出的原子在塞曼减速器中被减速，然后被加载到一个磁光阱中。若干秒后我们在1 mK温度， $6 \times 10^{11} \text{ cm}^{-3}$ 密度下采集到一个由 10^{10} 个原子组成的原子云。这些原子随后被偏振梯度冷却若干毫秒至50 μK ，并被光泵抽运至 $F=1$ 的基态，原子平均布居于三个磁子能级上。然后我们关闭所有的激光束，并用磁场将原子限制在“4 Dee”阱^[14]中。只有处于 $M_F = -1$ 态的原子，其磁偶极矩与磁场方向（被选作量子化轴）相反，被捕获于非对称的谐振势阱中。这个磁过滤使所有的样品原子都处于同一原子态（图1b中的量子态 $|1\rangle$ ），这就使下文所述的原子绝热光学制备和对原子云最低限度的加热成为可能。 [英文](#)

接下来我们将原子蒸发制冷38秒至玻色-爱因斯坦凝聚的临界转变温度 T_c 。调整磁场，绝热地减小势阱的梯度。这样所获得的势阱沿4 Dee势阱对称轴（ z ）方向的频率 $f_z = 21 \text{ Hz}$ ，横向频率 $f_x = f_y = 69 \text{ Hz}$ 。偏置场平行于 z 轴，为11 G。当温度完全低于 T_c ，我们只剩下处于凝聚态的一百万到两百万个原子。在这些参数下，转变发生在 $T_c = 435 \text{ nK}$ ，原子云峰值密度为 $5 \times 10^{12} \text{ cm}^{-3}$ 。 [英文](#)

我们现在来加一线偏振激光束，即耦合光束，将之调谐至无粒子分布的超精细态 $|2\rangle$ 和 $|3\rangle$ 之间的跃迁（图1b）。该光束将态 $|2\rangle$ 和 $|3\rangle$ 相耦合，从而对一更弱的调谐在态 $|1\rangle \rightarrow |3\rangle$ 跃迁的探测激光光束（左旋圆偏振）产生了量子干涉。在耦合激光和探测激光同时存在时，原子的稳定本征态（“暗”态）是两个超精细基态 $|1\rangle$ 和 $|2\rangle$ 的相干叠加。概率幅比值被设置为两激光对所激发的原子偶极矩的贡献恰好相抵消。量子干涉发生在探测频率的一狭窄的范围内，宽度由耦合激光功率决定。 [英文](#)

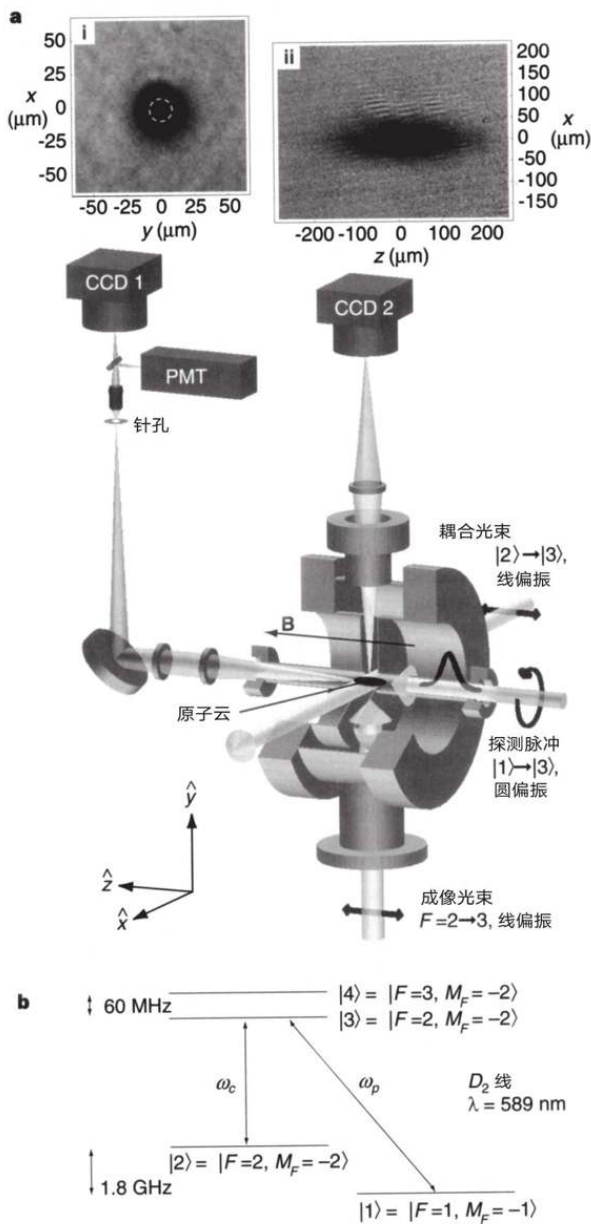


图1．实验装置图。—“耦合”激光束沿 x 轴传播，其线偏振方向 z 轴上加有11 G的偏置场。“探测”激光脉冲沿 z 轴传播，为左旋圆偏振。利用摄像机CCD1前的转向镜，我们可以引导探测光速进入摄像机或者进入光电倍增管（PMT）。对于脉冲延迟的测量，我们在成像光路中一个外部的成像平面上放置一个针孔，并选择探测光束在原子云中心直径为 $15 \mu\text{m}$ 的小区域（插图（i）中虚线圆所示）。脉冲延迟通过PMT测量。沿 y 轴传播的成像光束被用来使原子云在CCD2上成像，以获得原子云在沿脉冲传播方向（ z 轴）上的长度，并以此来确定光速。插图（ii）为降温至450 nK的原子，即在临界温度 T_c 以上15 nK。（注意该成像光束不能与探测光束或者耦合光束同时打开）。原子云的位置和在 x 和 y 两横向上的直径由CCD1测得。插图（i）为一凝聚态的成像图。

基于本文典型参数所确定的谐振频率，图2a为计算所得的探测光束透射率随其频率失谐的变化曲线。当 $|1\rangle \rightarrow |2\rangle$ 跃迁不存在失相时，量子干涉是完美的，在线中心，透射率应该是1。图2b给出了探测光束的折射率与失谐的函数关系。由于我们的纳开温度样品中 $|1\rangle \rightarrow |2\rangle$ 跃迁时非常小的多普勒展宽，施加非常小的耦合强度都会导致一个宽度比 $|1\rangle \rightarrow |3\rangle$ 跃迁的自然线宽窄很多的透明度峰。相应地，色散曲线比通过其他任何技术所获得的都更陡，这也就导致了本文所述的前所未有的极低群速度。电磁脉冲传播的群速度 v_g 为^[16-19]：

$$v_g = \frac{c}{n(\omega_p) + \omega_p \frac{dn}{d\omega_p}} \approx \frac{\hbar c \epsilon_0}{2\omega_p} \frac{|\Omega_c|^2}{|\mu_{13}|^2 N} \quad (1)$$

其中， $n(\omega_p)$ 为探测频率 ω_p (rad·s⁻¹)时的折射率， $|\Omega_c|^2$ 为耦合激光的拉比频率的平方，它随光强线性变化， μ_{13} 为态 $|1\rangle$ 和 $|3\rangle$ 间的电偶极矩矩阵元， N 为原子数密度， ϵ_0 为自由空间的介电常数。在线中央，折射率为1，等式(1)分母中的第二项的影响超过第一项，占主导地位。折射率图谱的一个重要特性是共振时群速度色散为0(参见文献16)，即 $d^2n/d\omega_p^2 = 0$ ，就最低阶来说，脉冲传播过程中保持波形不变。所建立的量子干涉允许脉冲传输通过在其他状态下透射系数仅为 e^{-110} (T_c 以下)的原子云，从而产生了极陡的色散图谱和极低的群速度。 [英文](#)

我们注意到图2中的曲线中心与探测共振频率偏离了0.6 MHz。这是由于耦合激光场使态 $|2\rangle$ 和 $|4\rangle$ 发生了耦合，从而能级 $|2\rangle$ 有交流斯塔克位移和与之相应的2→3跃迁的谱线位移。由于透明度峰值和等于1的折射率是在两光子共振时获得的，这就导致1→3跃迁共振频率下的折射率不为1。二者之间的差别与交流斯塔克位移成比例，也因此与耦合激光强度成比例，这点对下文所述的预估非线性折射率至关重要。 [英文](#)

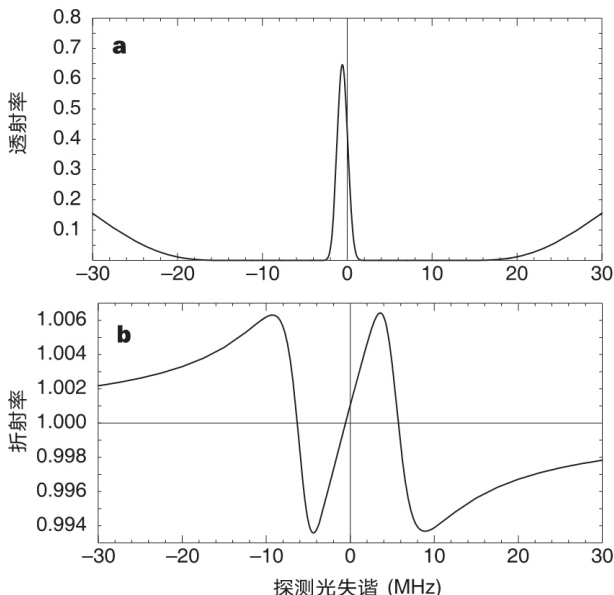


图2．探测光失谐的影响。**a**，透射率曲线。计算所得的探测透射率与激光频率相对原子云从 $|1\rangle \rightarrow |3\rangle$ 共振失谐的函数关系，该原子云被降温至450 nK，峰值密度为 $3.3 \times 10^{12} \text{ cm}^{-3}$ ，长度为229 μm （对应图1a中插图（ii）的原子云）。耦合激光与 $|2\rangle \rightarrow |3\rangle$ 的跃迁共振，功率密度为52 $\text{mW} \cdot \text{cm}^{-2}$ 。**b**，折射率曲线。计算所得的折射率与**a**中相同参数下探测光失谐的函数关系。达到共振时斜率的陡度与投射光脉冲的群速度成反比，并且由耦合激光强度所控制。要注意到，通过耦合激光场，态 $|2\rangle$ 和 $|4\rangle$ 产生耦合所造成的 $|2\rangle \rightarrow |3\rangle$ 跃迁的交流斯塔克位移的存在，导致透射率曲线的中心与折射率曲线的中心相差0.6 MHz。折射率曲线的偏移引起了文中所述的非线性折射率现象。 [英文](#)

实验图示如图1a所示。直径2.5 mm的耦合光束沿x轴传播，其线偏振方向平行于磁场 $\mathbf{B}$ 。探测光束直径0.5 mm、 σ^- 偏振，沿z轴传播。原子云在横向x, y方向的尺寸和位置由探测光束通过原子云后成像在电荷耦合器件（CCD）摄像机上的透射率剖面获得。插图（i）为一凝聚态的图像。当原子在调谐至与共振频率接近的5 $\text{mW} \cdot \text{cm}^{-2}$ 的探测光束中暴露10 μs 的过程中，另一55 $\text{mW} \cdot \text{cm}^{-2}$ 的耦合激光光束同时存在。 $f / 7$ 成像光学受衍射限制分辨率为7 μm 。 [英文](#)

在脉冲延迟的实验中，利用一针孔（置于透镜系统的外成像面）来只选择那些通过原子云中心15 μm 的部分探测光束，这部分原子柱的数密度最大。针孔的轮廓在插图（i）中以虚线圆标记出。 [英文](#)

耦合光束和探测光束都源于相同的染料激光。耦合激光器的频率由一声光调制器（AOM）设定为 $|2\rangle \rightarrow |3\rangle$ 的共振频率。这里我们将塞曼位

移和上文所提到的交流斯塔克位移都考虑在内。 [英文](#)

相应的探测共振频率由测量探测光束的透射率与频率的函数关系得出。我们运用一快速频率扫描，在50 μs 内扫描32 MHz，通过透射峰值来确定共振。扫描受另一AOM控制。然后将频率固定在共振频率，探测脉冲的时域波形就由控制AOM的无线电频率驱动来产生。所得脉冲是一个近高斯分布，半高宽为2.5 μs 。拉比频率 $\Omega_p = 0.20$ A时的峰值功率为1 $\text{mW}\cdot\text{cm}^{-2}$ 。这里取爱因斯坦自激系数A为 $6.3 \times 10^7 \text{ rad}\cdot\text{s}^{-1}$ 。为避免脉冲失真，我们给予其足够的持续时间来使其傅里叶分量包含在透明度峰之中。 [英文](#)

在耦合光束打开4 μs 之后探测脉冲沿z轴发射（耦合场保持打开100 μs ）。由于上文所讨论的磁过滤，所有的原子最初都处于 $|1\rangle$ 态，只有耦合激光存在时，这是一个暗态。当接收到光脉冲时，原子绝热演化，导致 $|2\rangle$ 态的概率幅与 $\Omega_p/(\Omega_p^2 + \Omega_c^2)^{1/2}$ 相等，其中 Ω_p 是探测光拉比频率。为了实现相干叠加态，能量从探测光脉冲的前沿传递到原子和耦合激光场。在探测光脉冲末端，原子绝热地回到原始态 $|1\rangle$ ，能量返回到探测脉冲后端，但没有净能量和动量转移到原子云。由于折射率等于1，在探测脉冲进入介质时电场不变。随着群速度降低，总能量密度必须提高才能保证单位面积功率不变。这种提高就体现在脉冲在原子云中传播时，能量在原子以及耦合激光场的储存。 [英文](#)

这些脉冲在穿过原子云后被一光电倍增管（响应时间为3 ns）所记录。光电倍增管的输出信号被150 MHz带宽的放大器放大，波形显示在一数字示波器上。在摄像机前放置一“转向”镜，我们就可以控制探测光束是射入摄像机还是射入光电倍增管中。 [英文](#)

探测光脉冲延迟测量的结果如图3所示。前面的脉冲是没有原子存在时的参考脉冲。脉冲穿过长度为229 μm 的原子云时被减慢，延迟了7.05 μs （见图1a，插图（ii））。由此可得光速为 $32.5 \text{ m}\cdot\text{s}^{-1}$ 。实验中我们使用的耦合激光强度为12 $\text{mW}\cdot\text{cm}^{-2}$ ，对应拉比频率为 $\Omega_c = 0.56$ A。原子云被冷却至450 nK（临界温度 T_c 以上15 nK）。峰值密度为 $3.3 \times 10^{12} \text{ cm}^{-3}$ ，原子总数为 3.8×10^6 。根据这些数据我们可以计算出在没有耦合激光时，脉冲透射系数为 e^{-63} 。实验中确实观察到当耦合

激光关闭时，探测脉冲完全被原子所吸收。本实验在低温下进行且原子云尺寸相对较小，由空间变化的塞曼位移引起的非均匀展宽（约20 kHz）可以忽略。 [英文](#)

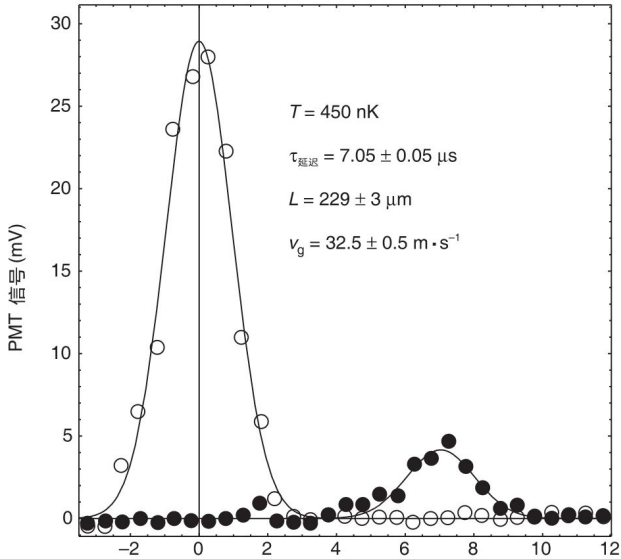


图3．脉冲延迟测量。前面的脉冲（空心圆）为系统中没有原子的参考脉冲。另一个脉冲（实心圆）在229 μm 长的原子云中被延迟7.05 μs （见图1a插图（ii））。相应的光速为32.5 $\text{m}\cdot\text{s}^{-1}$ 。曲线为测量脉冲的高斯拟合。 [英文](#)

沿 z 方向的原子云尺寸通过另一CCD摄像机捕获。为了达到这个目的，我们运用了另一独立的1 $\text{mW}\cdot\text{cm}^{-2}$ 的激光束沿垂直的 y 轴传播，并调谐到比 $F=2\rightarrow 3$ 跃迁低20 MHz。原子在10 μs 的曝光成像之前，先被泵到 $F=2$ 的基态10 μs 。我们使用衍射极限 $f/5$ 的光学器件在原子云之后对激光束的纵向透射率剖面进行成像。一个例子如图1a插图（ii）所示，其中由云的椭圆轮廓可清楚看见磁阱的不对称性。值得注意的是，成像激光不会与耦合激光及探测脉冲同时施加，并且对于每个记录的脉冲或CCD图片，都加载一新的原子云。 [英文](#)

我们在原子冷却到温度2.5 μK 和50 μK 之间测量了一系列脉冲延迟和相应的云尺寸。从这些数据对中，我们获得了相应的传播速度（图4）。空心圆对应耦合光强52 $\text{mW}\cdot\text{cm}^{-2}$ ($\Omega_c=1.2A$)。光速与原子数密度成反比（等式（1）），而原子数密度随温度降低而增大，当凝聚态形成时原子数密度进一步增加。实心圆对应耦合光强12 $\text{mW}\cdot\text{cm}^{-2}$ 。与等式（1）一致，可以看到耦合光强的降低引起群速度的减小。在最

初制备的几乎纯净的玻色-爱因斯坦凝聚态（凝聚比率大于等于90%）原子云中，我们获得了 $17 \text{ m} \cdot \text{s}^{-1}$ 的光脉冲传播速度。在脉冲传播过程中和传播后原子云是否保持凝聚不在本文讨论范围之内。 [英文](#)

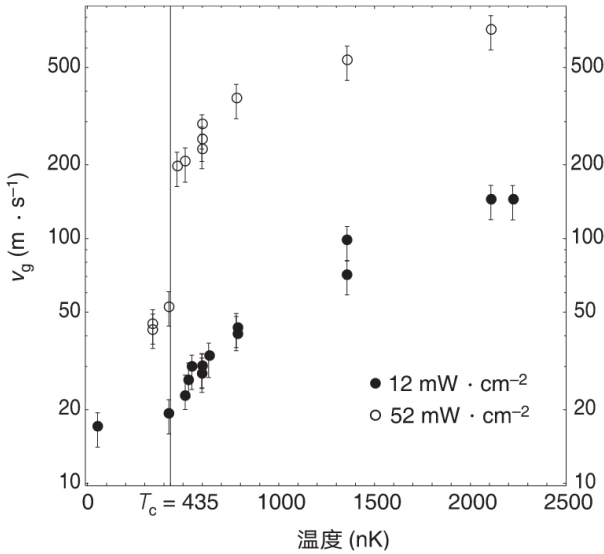


图4．光速与原子云温度的关系。由于原子数密度的增大，光速随温度的降低而降低。空心圆对应耦合光强 $52 \text{ mW} \cdot \text{cm}^{-2}$ ，实心圆对应耦合光强 $12 \text{ mW} \cdot \text{cm}^{-2}$ 。温度 T_c 标记出了玻色-爱因斯坦凝聚的临界转变温度。 T_c 以下的群速度减小是由形成凝聚态时原子云密度增大而引起。通过成像测量，我们得到200 nK时最大的原子数密度为 $8 \times 10^{13} \text{ cm}^{-3}$ 。密集凝聚态成分占所有原子的60%，并且总原子数密度是 T_c 时非凝聚态云密度的16倍。50 nK时的光速测量是在凝聚分数 $\geq 90\%$ 的云中进行的。由于态 $|4\rangle$ 造成的有限的退相率不允许脉冲穿过最密集的云。这个问题可以通过文中所述的调谐激光至 D_1 线的方法来解决。 [英文](#)

由耦合激光激发的 $|2\rangle \rightarrow |4\rangle$ 态的跃迁（耦合激光与该跃迁之间存在60 MHz失谐），使得所建立的 $|1\rangle$ 和 $|2\rangle$ 态的相干具有一个有限衰变率，并限制了探测光脉冲的透射。退相率与耦合激光的功率密度成比例，我们预期并发现，探测脉冲具有一个透射率峰值，该值不受耦合强度以及随此强度线性减小的速度的影响。退相时间由透射率-脉冲延迟的半对数曲线的斜率决定^[19]。在耦合光强为 $12 \text{ mW} \cdot \text{cm}^{-2}$ 时，对于温度刚刚超过 T_c 的原子云，我们测量到退相时间为9 μs 。 [英文](#)

巨克尔非线性在量子光学领域具有很大的吸引力，例如光学压缩、量子非破坏性以及非定域性等方面的研究。近期的研究还指出，这些现象很可能通过电磁感应透明来获得^[20]。本文报道了（据我们所知）首次对这样一种非线性的测量。零失谐探测光的折射率表达式为

$n = 1 + (n_2 I_c)$ ，其中 I_c 为耦合激光强度， n_2 为交叉相位非线性折射率。正如图2b所示，非线性项 $n_2 I_c$ 等于探测光在共振时的折射率曲线斜率与耦合激光激发的 $|2\rangle \rightarrow |3\rangle$ 跃迁的交流斯塔克位移之积。因此 n_2 可以用以下公式表示（见等式（1））：

$$n_2 = \frac{\Delta\omega_s}{I_c} \frac{dn}{d\omega_p} \approx \frac{1}{2\pi} \frac{\Delta\omega_s}{I_c} \frac{\lambda}{v_g} \quad (2)$$

其中 $\Delta\omega_s$ 为交流斯塔克位移，与 I_c 成比例， λ 为探测跃迁的光波长。当耦合激光强度为 $40 \text{ mW}\cdot\text{cm}^{-2}$ 时我们测量到 $-1.3 \times 10^6 \text{ rad}\cdot\text{s}^{-1}$ 的交流斯塔克位移。而对于测量所得的 $17 \text{ m}\cdot\text{s}^{-1}$ 的群速度（图4），可得非线性折射率为 $0.18 \text{ cm}^2\cdot\text{W}^{-1}$ 。该非线性折射率是在冷铯原子中相应值的 10^6 倍[21]。

英文

应用上文所述的可避免 $|1\rangle - |2\rangle$ 退相率的系统（通过调谐至钠 D_1 线而获得），可以对这里所使用的方法进一步发展以得出在建立电磁感应透明过程中发生的双凝聚态碰撞诱导失相率（参见文献22和23）。在这种情况下，态 $|3\rangle$ 概率幅的平方在脉冲传播过程中可以保持在 10^{-5} 以下，因此不存在凝聚态加热。由于我们装置频率稳定性的提高以及耦合强度的减小，更低的光速也是可能实现的，可能是几厘米每秒的量级，可与玻色-爱因斯坦凝聚中的音速相比。在此条件下我们预期光脉冲传播通过凝聚体时有声子被激发。通过谨慎调谐另一激光束至 $|2\rangle \rightarrow |4\rangle$ 跃迁，应该有可能在单光子水平上演示光学开关[24]。最后本文指出，光束在原子云传播过程中，光脉冲在 z 方向被压缩，比率为 c/v_g 。对于本实验所采用的参数，这导致脉冲的空间范围仅为 $43 \text{ }\mu\text{m}$ 。

英文

（崔宁 翻译；石锦卫 审稿）

Observation of Coherent Optical Information Storage in an Atomic Medium Using Halted Light Pulses

C. Liu *et al.*

Laser light shining on an opaque medium can sometimes make it transparent to other light, a phenomenon known as electromagnetically induced transparency. The optical properties of the medium change so dramatically that light pulses can be slowed and compressed by many orders of magnitude. Here Chien Liu and colleagues report on experiments in which they used the effect to bring laser pulses to a complete standstill in a cold gas of sodium atoms held in a magnetic trap. They also show that information may be frozen into the atomic medium for as long as 1 microsecond, and then recovered. Liu and colleagues suggest that this technique could be useful in the development of quantum computers and other quantum information systems.

[中文](#)

Electromagnetically induced transparency¹⁻³ is a quantum interference effect that permits the propagation of light through an otherwise opaque atomic medium; a “coupling” laser is used to create the interference necessary to allow the transmission of resonant pulses from a “probe” laser. This technique has been

used⁴⁻⁶ to slow and spatially compress light pulses by seven orders of magnitude, resulting in their complete localization and containment within an atomic cloud⁴. Here we use electromagnetically induced transparency to bring laser pulses to a complete stop in a magnetically trapped, cold cloud of sodium atoms. Within the spatially localized pulse region, the atoms are in a superposition state determined by the amplitudes and phases of the coupling and probe laser fields. Upon sudden turn-off of the coupling laser, the compressed probe pulse is effectively stopped; coherent information initially contained in the laser fields is “frozen” in the atomic medium for up to 1 ms. The coupling laser is turned back on at a later time and the probe pulse is regenerated: the stored coherence is read out and transferred back into the radiation field. We present a theoretical model that reveals that the system is self-adjusting to minimize dissipative loss during the “read” and “write” operations. We anticipate applications of this phenomenon for quantum information processing. 中文

WITH the coupling and probe lasers used in the experiment, the atoms are accurately modelled as three-level atoms interacting with the two laser fields (Fig. 1a). Under perfect electromagnetically-induced transparency (EIT) conditions (two-photon resonance), a stationary eigenstate exists for the system of a three-level atom and resonant laser fields, where the atom is in a “dark”, coherent superposition of states $|1\rangle$ and $|2\rangle$:

$$|D\rangle = \frac{\Omega_c|1\rangle - \Omega_p|2\rangle \exp[i(\mathbf{k}_p - \mathbf{k}_c) \cdot \mathbf{r} - i(\omega_p - \omega_c)t]}{\sqrt{\Omega_c^2 + \Omega_p^2}} \quad (1)$$

Here Ω_p and Ω_c are the Rabi frequencies, $\mathbf{k}_p$ and $\mathbf{k}_c$ the wavevectors, and ω_p and ω_c the optical angular frequencies of the probe and coupling lasers, respectively. The Rabi frequencies are defined as $\Omega_{p,c} \equiv e \mathbf{E}_{p,c} \mathbf{r}_{13,23} / \hbar$, where e is the electron charge, $\mathbf{E}_{p,c}$ are the

slowly varying envelopes of probe and coupling field amplitudes, and $e \mathbf{r}_{13,23}$ are the electric dipole moments of the atomic transitions. The dark state does not couple to the radiatively decaying state $|3\rangle$, which eliminates absorption of the laser fields¹⁻³. 中文

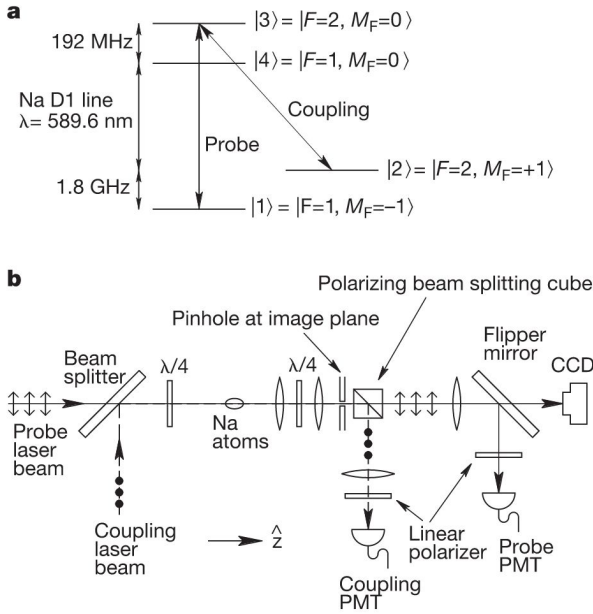


Fig. 1. Experimental set-up and procedure. **a**, States $|1\rangle$, $|2\rangle$ and $|3\rangle$ form the three-level EIT system. The cooled atoms are initially magnetically trapped in state $|1\rangle = |3S, F=1, M_F=-1\rangle$. Stimulated photon exchanges between the probe and coupling laser fields create a “dark” superposition of states $|1\rangle$ and $|2\rangle$, which renders the medium transparent for the resonant probe pulses. **b**, We apply a 2.2-mm diameter, σ^- -polarized coupling laser, resonant with the $|3S, F=2, M_F=+1\rangle \rightarrow |3P, F=2, M_F=0\rangle$ transition, and a co-propagating, 1.2-mm diameter σ^+ -polarized probe pulse tuned to the $|3S, F=1, M_F=-1\rangle \rightarrow |3P, F=2, M_F=0\rangle$ transition. The two laser beams start out with orthogonal linear polarizations (two-headed arrows and filled circles show the directions of linear polarization of the probe and coupling lasers, respectively). They are combined with a beam splitter, circularly polarized with a quarter-wave plate ($\lambda/4$), and then injected into the atom cloud. After leaving the cloud, the laser beams pass a second quarter-wave plate and regain their original linear polarizations before being separated with a polarizing beam-splitting cube. The atom cloud is imaged first onto an external image plane and then onto a CCD (charge-coupled device) camera. A pinhole is placed in the external image plane and positioned at the centre of the cloud image. With the pinhole and flipper mirror in place, only those portions of the probe and coupling laser beams that have passed through the central region of the cloud are selected and monitored simultaneously by two photomultiplier tubes (PMTs). States $|1\rangle$ and $|2\rangle$ have identical first-order Zeeman shifts so the two-photon resonance is maintained across the trapped atom clouds. Cold atoms and co-propagating lasers eliminate Doppler effects.

However, off-resonance transitions to state $|4\rangle$ prevent perfect transmission of the light pulses in this case. [中文](#)

Atoms are prepared (magnetically trapped) in a particular internal quantum state $|1\rangle$ (Fig. 1a). The atom cloud is first illuminated by a coupling laser, resonant with the $|2\rangle-|3\rangle$ transition. With only the coupling laser on and all atoms in $|1\rangle$, the system is in a dark state (equation (1) with $\Omega_p=0$). A probe laser pulse, tuned to the $|1\rangle-|3\rangle$ transition and co-propagating with the coupling laser, is subsequently sent through the atomic medium. Atoms within the pulse region are driven into the dark-state superposition of states $|1\rangle$ and $|2\rangle$, determined by the ratio of the instantaneous Rabi frequencies of the laser fields (equation (1)). [中文](#)

The presence of the coupling laser field creates transparency, a very steep refractive index profile, and low group velocity, V_g , for the probe pulse¹⁻¹⁰. As the pulse enters the atomic medium, it is spatially compressed by a factor c / V_g whereas its peak electric amplitude remains constant during the slow-down^{4,7}. [中文](#)

The experiment is performed with the apparatus described in refs 4 and 11. Figure 1 shows the new optical set-up and atomic energy levels involved. A typical cloud of 11 million sodium atoms is cooled to 0.9 μK , which is just above the critical temperature for Bose-Einstein condensation. The cloud has a length of 339 μm in the z direction, a width of 55 μm in the transverse directions, and a peak density of 11 μm^{-3} . Those portions of the co-propagating probe and coupling laser beams that have passed through the 15- μm -diameter centre region of the cloud are selected and monitored simultaneously by two photomultiplier tubes (PMTs). [中文](#)

Figure 2a shows typical signals detected by the PMTs. The dashed curve is the measured intensity of the coupling laser, which is turned on a few microseconds before the probe pulse. The open circles indicate a gaussian-shaped reference probe pulse recorded in the

absence of atoms (1 / e full width is 5.70 μs). The filled circles show a probe pulse measured after it has passed through a cold atom cloud, and the solid curve is a gaussian fit to the data. The delay of this probe pulse, relative to the reference pulse, is 11.8 μs corresponding to a group velocity of 28 m s⁻¹, a reduction by a factor of 10⁷ from its vacuum value. The measured delay agrees with the theoretical prediction of 12.2 μs based on a measured coupling Rabi frequency Ω_c of 2.57 MHz $\times 2\pi$ and an observed atomic column density of 3,670 μm^{-2} .

- 2. 中文

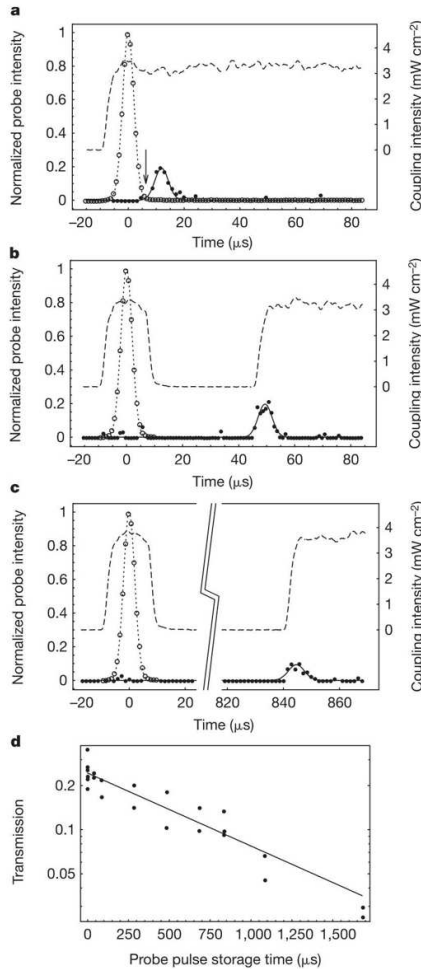


Fig. 2. Measurements of delayed and revived probe pulses. Open circles (fitted to the dotted gaussian curves) show reference pulses obtained as the average of 100 probe pulses recorded in the absence of atoms. Dashed curves and filled circles (fitted to the solid gaussian curves) show simultaneously measured intensities of coupling and probe pulses that have propagated

under EIT conditions through a 339- μm -long atom cloud cooled to 0.9 μK . The measured probe intensities are normalized to the peak intensity of the reference pulses (typically, $\Omega_p / \Omega_c = 0.3$ at the peak). **a**, Probe pulse delayed by 11.8 μs . The arrow at 6.3 μs indicates the time when the probe pulse is spatially compressed and contained completely within the atomic cloud. (The intersection of the back edge of the reference pulse and the front edge of the delayed pulse defines a moment when the tail of the probe pulse has just entered the cloud and the leading edge is just about to exit.) **b**, **c**, Revival of a probe pulse after the coupling field is turned off at $t = 6.3 \mu\text{s}$ and turned back on at $t = 44.3 \mu\text{s}$ and $t = 839.3 \mu\text{s}$, respectively. During the time interval when the coupling laser is off, coherent information imprinted by the probe pulse, is stored in the atomic medium. Upon subsequent turn-on of the coupling field, the probe pulse is regenerated through coherent stimulation. The time constants for the probe and coupling PMT amplifiers are 0.3 μs and 3 μs , respectively. The actual turn on / off time for the coupling field is 1 μs , as measured with a fast photodiode. **d**, Measured transmission of the probe pulse energy versus storage time. The solid line is a fit to the data, which gives a $1 / e$ decay time of 0.9 ms for the atomic coherence. [中文](#)

At time $t = 6.3 \mu\text{s}$, indicated by the arrow in Fig. 2a, the probe pulse is spatially compressed and contained completely within the atomic cloud. The probe pulse in free space is 3.4 μm long and contains 27,000 photons within a 15- μm diameter at its centre. It is compressed in the atomic medium to match the size of the cloud (339 μm), and the remaining optical energy in the probe field is only $1 / 400$ of a free-space photon. Essentially all of the probe energy has been transferred through stimulated emission into the coupling laser field and the atomic medium, and coherent optical information has been imprinted on the atoms (equation (1)). [中文](#)

To store this coherent information, we turn off the coupling field abruptly when the probe pulse is contained within the cloud. The stored information is read out at a later time by turning the coupling laser back on. A result is shown in Fig. 2b. The dashed curve shows the coupling laser's turn-off at $t = 6.3 \mu\text{s}$ and its subsequent turn-on at 44.3 μs . The filled circles represent the measured probe intensity. As seen from the data, when the coupling laser is turned back on the probe pulse is regenerated: we can stop and controllably regenerate the probe pulse. Similar effects have been predicted in a recent theoretical paper¹². [中文](#)

When the probe pulse is contained within the medium, the coherence of the laser fields is already imprinted on the atoms. As the coupling laser is turned off, the probe field is depleted to maintain the dark state (equation (1)) and (negligible) atomic amplitude is transferred from state $|1\rangle$ to state $|2\rangle$ through stimulated photon exchange between the two light fields. Because of the extremely low energy remaining in the compressed probe pulse, as noted above, it is completely depleted before the atomic population amplitudes have changed by an appreciable amount. When the coupling laser is turned back on, the process reverses and the probe pulse is regenerated through stimulated emission into the probe field. It propagates subsequently under EIT conditions as if the coupling beam had never been turned off. [中文](#)

During the storage time, information about the amplitude of the probe field is contained in the population amplitudes defining the atomic dark states. Information about the mode vector of the probe field is contained in the relative phase between different atoms in the macroscopic sample. The use of cold atoms minimizes thermal motion and the associated smearing of the relative phase during the storage time. (We obtain storage times that are up to 50 times larger than the time it takes an atom to travel one laser wavelength. As seen from equation (1), the difference between the wavevectors of the two laser fields determines the wavelength of the periodic phase pattern imprinted on the medium, which is 10^5 times larger than the individual laser wavelengths.) [中文](#)

The regenerated probe pulse in Fig. 2b has the same shape as the “normal” EIT pulse shown in Fig. 2a. Figure 2c shows a case where the optical coherence is stored in the atomic medium for more than 800 μs before it is read out by the coupling laser. Here the amplitude of the revived probe pulse is reduced compared to that of the pulse in Fig. 2b. Figure 2d shows the measured transmission for a series of

pulses as a function of their storage time in the atom cloud. The data are consistent with an exponential decay with a $1/e$ decay time of 0.9 ms, comparable to the calculated mean free time of 0.5 ms between elastic collisions in the atom cloud with a density of $11 \mu\text{m}^{-3}$. Further studies of the decoherence mechanisms are planned but are beyond the scope of this Letter. [中文](#)

We have verified experimentally that the probe pulse is regenerated through stimulated rather than spontaneous emission. To do this, we prepared all atoms in state $|2\rangle$ and subsequently turned on the coupling laser alone. The coupling laser was completely absorbed for tens of microseconds without generating any signal in the probe PMT.

[中文](#)

In Fig. 3a–c, we show three PMT signal traces recorded under similar conditions except that we vary the intensity, I_{c2} , of the coupling laser when it is turned back on. When I_{c2} is larger than the original coupling intensity, I_{c1} , the amplitude of the revived probe pulse increases and its temporal width decreases (Fig. 3a). For $I_{c2} < I_{c1}$, the opposite occurs (Fig. 3c). These results support our physical picture of the process. The stored atomic coherence dictates the ratio of the Rabi frequencies of the coupling and revived probe fields, as well as the spatial width of the regenerated pulse. In Fig. 3d we show that with a large I_{c2} , the peak intensity of the revived probe pulse exceeds that of the original input pulse by 40%. [中文](#)

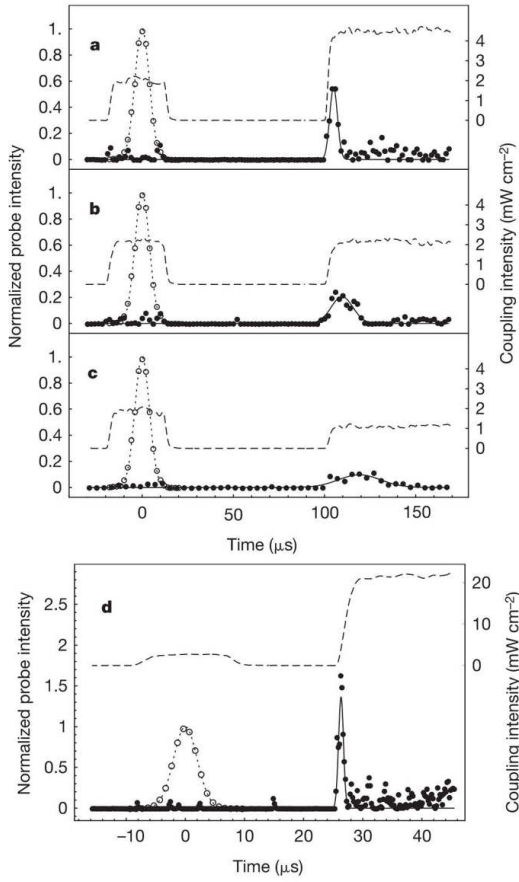


Fig. 3. Measurements of revived probe pulses for varying intensities (I_{c2}) of the second coupling pulse. The intensity (I_{c1}) of the first coupling pulse is held constant. **a–c**, The figures are recorded for I_{c2} / I_{c1} ratios of 2, 1, and 0.5, respectively. A series of data show that the height and the inverse temporal width of the revived pulses are each proportional to I_{c2} . These observations are consistent with our physical picture. Because the atomic coherence dictates the ratio of the Rabi frequencies for the coupling and revived probe fields (equation (1)), the intensity of the regenerated probe pulse is proportional to the intensity of the coupling laser when it is turned back on. Furthermore, the spatial width of the revived pulse is determined by the distribution of the atomic coherence and is thus the same as the spatial extent of the original compressed pulse. The group velocity of the probe pulse under EIT conditions is proportional to the coupling intensity^{4,7}. With a larger (smaller) I_{c2} , the revived probe pulse acquires a proportionally larger (smaller) group velocity, which causes its temporal width to be inversely proportional to I_{c2} . Panel **d** shows that the intensity of the revived probe pulse can exceed that of the original input pulse, in this instance by 40%. (The observed peak-to-peak fluctuation of laser intensity is less than 10%.) The energy in the revived probe pulses is the same in all panels **a–d**, owing to the fact that the total stored amplitude of state $|2\rangle$ atoms (available to stimulate photons into the probe field) is the same in all cases. Meanings of lines and symbols as in Fig. 2. 中文

Dissipationless pulse storage and revival processes are only possible if the ratio between the rates of dissipative and coherence-preserving events is small. When the coupling field is increased or decreased quickly compared to the duration of the probe pulse (τ) but slowly compared to $1 / \Gamma$, this ratio is equal to (Z.D. and L.V.H., manuscript in preparation)

$$\frac{2\Gamma}{\Omega_c^2 + \Omega_p^2} \left(\frac{\dot{\Omega}_p}{\Omega_p} - \frac{\dot{\Omega}_c}{\Omega_c} \right) \quad (2)$$

where Γ is the spontaneous decay rate from state $|3\rangle$. Our numerical simulations show that the probe field is constantly adjusting to match the changes in the coupling field in such a way that the terms in brackets in equation (2) nearly cancel^{13,14}. Even for turn-off times faster than $1 / \Gamma$, we can show that there is no decay of the coherence between states $|1\rangle$ and $|2\rangle$ as long as $\tau \gg \Gamma / (\Omega_{c0}^2 + \Omega_{p0}^2)$; here Ω_{c0} and Ω_{p0} are the Rabi frequencies before the coupling turn-off. (The adiabatic requirement introduced in ref. 12 as necessary for non-dissipative behaviour is much too strict. That requirement would inevitably break down for low coupling laser powers during turn-on or turn-off.) 中文

We have demonstrated experimentally that coherent optical information can be stored in an atomic medium and subsequently read out by using the effect of EIT in a magnetically trapped, cooled atom cloud. We have experimentally verified that the storage and read-out processes are controlled by stimulated photon transfers between two laser fields. Multiple read-outs can be achieved using a series of short coupling laser pulses. In Fig. 4a and b we show measurements of double and triple read-outs spaced by up to hundreds of microseconds. Each of the regenerated probe pulses contains part of the contents of the “atomic memory”, and for the parameters chosen, the memory is depleted after the second pulse and after the third pulse. 中文

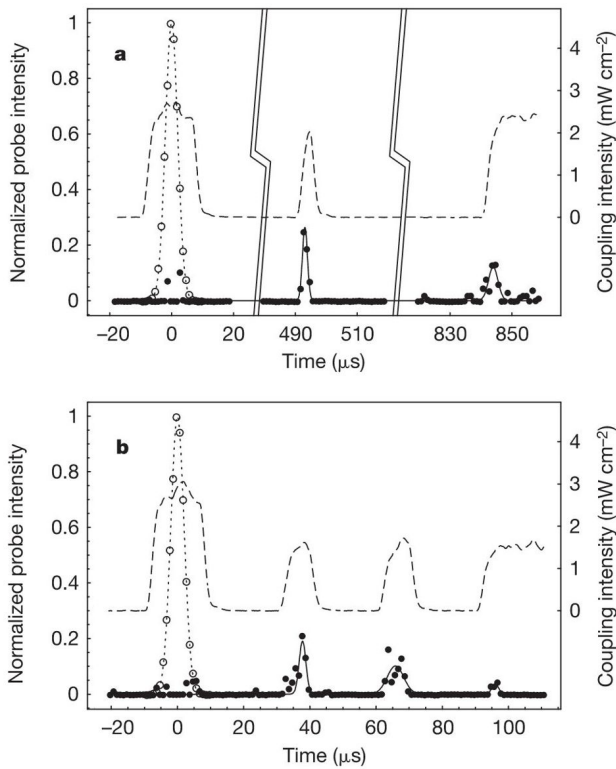


Fig. 4. Measurements of double and triple read-out of the atomic memory. To deplete the atomic memory in these cases, we use two (a) and three (b) short coupling pulses. The total energy in the two (three) revived probe pulses is measured to be the same as the energy in the single revived probe pulse obtained with a single, long coupling laser pulse (as used in Figs 2 and 3). Meanings of lines and symbols as in Fig. 2. 中文

We believe that this system could be used for quantum information transfer; for example, to inter-convert stationary and flying qubits¹⁵. By injection of multiple probe pulses into a Bose–Einstein condensate—where we expect that most atomic collisions are coherence-preserving—and with use of controlled atom–atom interactions, quantum information processing may be possible during the storage time. 中文

(409, 490-493; 2001)

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Received 13 October; accepted 17 November 2000.

References:

1. Harris, S. E. Electromagnetically induced transparency. *Phys. Today* **50**, 36-42 (1997).
2. Scully, M. O. & Zubairy, M. S. *Quantum Optics* (Cambridge Univ. Press, Cambridge, 1997).
3. Arimondo, E. in *Progress in Optics* (ed. Wolf, E.) 257-354 (Elsevier Science, Amsterdam, 1996).
4. Hau, L. V., Harris, S. E., Dutton, Z. & Behroozi, C. H. Light speed reduction to 17 metres per second in an ultracold atomic gas. *Nature* **397**, 594-598 (1999).
5. Kash, M. M. *et al.* Ultraslow group velocity and enhanced nonlinear optical effects in a coherently driven hot atomic gas. *Phys. Rev. Lett.* **82**, 5229-5232 (1999).
6. Budker, D., Kimball, D. F., Rochester, S. M. & Yashchuk, V. V. Nonlinear magneto-optics and reduced group velocity of light in atomic vapor with slow ground state relaxation. *Phys. Rev. Lett.* **83**, 1767-1770 (1999).
7. Harris, S. E., Field, J. E. & Kasapi, A. Dispersive properties of electromagnetically induced transparency. *Phys. Rev. A* **46**, R29-R32 (1992).
8. Grobe, R., Hioe, F. T. & Eberly, J. H. Formation of shape-preserving pulses in a nonlinear adiabatically integrable system. *Phys. Rev. Lett.* **73**, 3183-3186 (1994).
9. Xiao, M., Li, Y.-Q., Jin, S.-Z. & Gea-Banacloche, J. Measurement of dispersive properties of electromagnetically induced transparency in rubidium atoms. *Phys. Rev. Lett.* **74**, 666-669 (1995).
10. Kasapi, A., Jain, M., Yin, G. Y. & Harris, S. E. Electromagnetically induced transparency: propagation dynamics. *Phys. Rev. Lett.* **74**, 2447-2450 (1995).
11. Hau, L. V. *et al.* Near-resonant spatial images of confined Bose-Einstein condensates in a 4-Dee magnetic bottle. *Phys. Rev. A* **58**, R54-R57 (1998).
12. Fleischhauer, M. & Lukin, M. D. Dark-state polaritons in electromagnetically induced transparency. *Phys. Rev. Lett.* **84**, 5094-5097 (2000).
13. Harris, S. E. Normal modes for electromagnetically induced transparency. *Phys. Rev. Lett.* **72**, 52-55 (1994).
14. Fleischhauer, M. & Manak, A. S. Propagation of laser pulses and coherent population transfer in dissipative three-level systems: An adiabatic dressed-state picture. *Phys. Rev. A* **54**, 794-803 (1996).
15. DiVincenzo, D. P. The physical implementation of quantum computation. Preprint quant-ph / 0002077 at $\langle$ <http://xxx.lanl.gov> $\rangle$ (2000).

Acknowledgements. We thank J. Golovchenko for discussions during which the idea of the rapid turn off and on of the coupling laser first emerged. We also thank M. Burns for critical reading of the manuscript. This work was supported by the Rowland Institute for Science, the Defense Advanced Research Projects Agency, the US Airforce Office of Scientific Research, and the US Army Research Office OSD Multidisciplinary University Research Initiative Program.

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运用停止光脉冲来观测原子介质中的相干光学信息存储

刘谦（音译）等

照射在不透明介质上的激光有时会使介质对其他光线透明，这种现象称为电磁感应透明。介质的光学性质变化非常显著，以至于光脉冲可以被放慢和压缩许多个数量级。本文中，刘谦（音译）与其同事们报道了使用这种效应的实验，在这些实验中，他们使激光脉冲完全停滞在磁阱中的冷钠原子气团中。他们还展示了信息可冻结在原子介质中长达1微秒，然后恢复。刘谦与其同事们认为这种技术可以用于量子计算机和其他量子信息系统的开发。 [英文](#)

电磁感应透明^[1-3]是一种量子干涉效应，它允许光在其他状态下非透明的原子介质中传播；“耦合”激光被用来产生必要的干涉，以实现从“探测”激光发出的共振脉冲的传输。这种技术^[4-6]已经被用于减缓及空间压缩光脉冲达七个数量级之多，从而导致其在原子云内的完全局域化和容纳^[4]。本文运用电磁感应透明来使激光脉冲在磁阱捕获的冷钠原子云中完全停止。在空间局域化脉冲区域内，原子处于由耦合激光场和探测激光场的振幅和相位所决定的叠加态。当突然关闭耦合激光时，压缩的探测光束会有效地停止；最初存储在激光场中的相干信息就被“冷冻”在原子介质中，最长可达1 ms。随后耦合激光被重新开启，探测脉冲便再次产生：所存储的相干信息被读取出来并转移回辐射场。本文提出了一个理论模型，揭示了该系统的自调节特征使得“读”和“写”操作过程中耗散损失最小。我们预期这种现象可以被应用于量子信息处理。 [英文](#)

英文

这里 Ω_p 和 Ω_c 分别为探测和耦合激光的拉比频率， $\mathbf{k}_p$ 和 $\mathbf{k}_c$ 为波矢， ω_p 和 ω_c 为光学角频率。拉比频率定义为 $\Omega_{p,c} = e\mathbf{E}_{p,c} \cdot \mathbf{r}_{13,23} / \hbar$ ，其中 e 为电子电荷， $\mathbf{E}_{p,c}$ 为探测和耦合场振幅的缓慢变化包络， $e\mathbf{r}_{13,23}$ 为原子跃迁的电偶极矩。暗态不会与辐射衰减态 $|3\rangle$ 耦合，从而抵消了激光场的吸收^[1-3]。

图1. 实验装置和实验过程。a, 量子态 $|1\rangle, |2\rangle, |3\rangle$ 构成一个三能级EIT系统。被降温的原子最初被磁阱捕获于态 $|1\rangle = |3S, F=1, M_F=-1\rangle$ 。探测和耦合激光场之间的受激光子交换产生了态 $|1\rangle$ 和 $|2\rangle$ 的“暗”叠加态, 这使得介质对共振探测脉冲是透明的。b, 我们施加一个直径2.2 mm的 σ^- 偏振耦合激光, 频率与 $|3S, F=2, M_F=+1\rangle \rightarrow |3P, F=2, M_F=0\rangle$ 态的跃迁共振, 还施加一个同向传播的, 1.2 mm直径, 频率调谐至 $|3S, F=1, M_F=-1\rangle \rightarrow |3P, F=2, M_F=0\rangle$ 跃迁的 σ^+ 偏振探测激光。两激光束以正交的线性偏振方向发出(双箭头和实心圆分别代表探测和耦合光束的偏振方向)。它们通过分束器合成, 经四分之一($\lambda/4$)波片形成圆偏振, 然后射入原子云。从原子云中射出后, 激光束又经过四分之一($\lambda/4$)波片, 在被偏振分束立方体分离之前重获原来各自的线偏振态。原子云首先成像在一外置的成像平面, 然后成像

在CCD（电荷耦合器件）摄像机上。一针孔被置于外置的成像平面上，位于云图像的中心。通过针孔和翻转镜的适当摆放，只有通过了云中心区域的探测和耦合激光光束被采集并且同时由两个光电倍增管（PMT）监测。量子态 $|1\rangle$ 和 $|2\rangle$ 有相同的一阶塞曼位移，所以双光子共振在被捕获的原子云中保持下来。冷原子和同向传播的激光消除了多普勒效应。但是，在这种情况下，由于存在到量子态 $|4\rangle$ 的非共振跃迁，光脉冲无法获得理想的透射率。 英文

原子制备（磁阱捕获）时处于一特定的内量子态 $|1\rangle$ （图1a）。原子云最初受一耦合激光辐射，与 $|2\rangle-|3\rangle$ 跃迁共振。只有耦合激光开启，并且所有的原子都处于 $|1\rangle$ 态时，系统处于暗态中（等式（1）中 $\Omega_p=0$ ）。一探测激光脉冲，被调谐至 $|1\rangle-|3\rangle$ 跃迁，与耦合激光同向传播，随后被发送穿过原子介质。在脉冲区域的原子被驱动至 $|1\rangle$ 和 $|2\rangle$ 的暗叠加态，该叠加态由激光场的瞬时拉比频率的比率决定（等式（1））。 英文

耦合激光场的存在产生了透明现象，并导致探测脉冲的折射率图谱变得非常陡峭，群速度 V_g 变得很低^[1-10]。当脉冲进入原子介质时，其空间尺寸被压缩了 c/V_g 倍，而在减速期间其峰值电子振幅保持恒定^[4,7]。 英文

实验装置如参考文献4和11所述。图1给出了新的光学装置以及所涉及的原子能级。一典型的原子云包含1,100万钠原子，它被冷却至0.9 μK ，刚好在玻色-爱因斯坦凝聚临界温度以上。原子云在 z 方向长339 μm ，横向宽度55 μm ，峰值密度为11 μm^{-3} 。选择同向传播的探测和耦合激光光束中通过原子云中心直径15 μm 区域的部分，并用两个光电倍增管（PMT）同时监测。 英文

图2a给出了PMT探测到的典型信号。虚线表示耦合激光的测量强度，比探测脉冲早几微秒打开。空心圆为没有原子存在时（1 / e全宽为5.70 μs ）所记录的高斯型参考探测脉冲。实心圆为探测脉冲通过一冷原子云后所测得的信号，实线为数据的高斯拟合。这个探测脉冲与参考脉冲相比的延迟为11.8 μs ，对应群速度为28 $\text{m}\cdot\text{s}^{-1}$ ，相当于真空中速度的1 / 10⁷。实验测得的延迟与理论预测值12.2 μs 相符合。该理论预测值是基于测量所得的耦合拉比频率 Ω_c （2.57 $\text{MHz} \times 2\pi$ ）以及观测所得的原子柱密度（3,670 μm^{-2} ）获得的。 英文

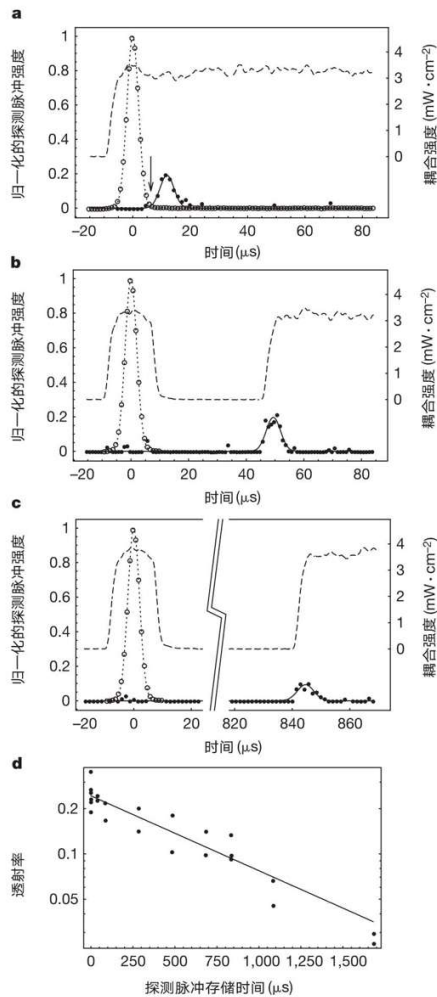


图2．探测脉冲延迟和再生的测量。空心圆（高斯拟合用点线表示）对应参考脉冲，为没有原子时所记录的100个探测脉冲的平均值。虚线和实心圆（高斯拟合用实线表示）对应应在EIT条件下同时测量耦合和探测脉冲经由339 μm 长，降温至0.9 μK 的原子云传播所得到的强度。测量所得的探测强度相对参考脉冲的峰值强度进行了归一化（一般地，峰值处的 $\Omega_p / \Omega_c = 0.3$ ）。**a**，探测脉冲延迟11.8 μs 。6.3 μs 处的箭头表示探测脉冲空间上被压缩并被完全包含在原子云中的时刻（参考脉冲的后沿与延迟脉冲的前沿之间的交叉点决定了脉冲尾部刚刚进入云而前沿又恰好要离开的时刻）。**b**，**c**，耦合场在 $t = 6.3$ μs 关闭，又分别在 $t = 44.3$ μs 和 $t = 839.3$ μs 重新开启之后探测脉冲的再生。在耦合激光关闭的时间间隔期间内，探测脉冲所携带的相干信息就存储在原子介质中。随着耦合场再次开启，探测脉冲通过相干激励再次产生。探测和耦合PMT放大器的时间常数分别为0.3 μs 和3 μs 。根据快速光电二极管的测量，耦合场的实际开启/关闭时间为1 μs 。**d**，测量所得的探测脉冲能量透射率与存储时间的关系。实线是对数据进行的拟合结果，给出了对于原子相干的 $1/e$ 衰减时间0.9 ms。 [英文](#)

当时间 $t = 6.3$ μs 时，如图2a中的箭头所示，探测脉冲空间上被压缩并被完全包含在原子云中。这个探测脉冲在自由空间中长3.4 μm ，在其

中心15 μm 直径范围内含有27,000个光子。为了与云尺寸（339 μm ）相匹配，它在原子介质中被压缩，且探测场所剩余的光能仅为自由空间光子的1 / 400。实质上来讲几乎所有的探测能量都通过受激辐射被转移至耦合激光场和原子介质，而相干光学信息也被印记于原子之上（等式（1））。 [英文](#)

为了存储这些相干信息，当探测脉冲刚好被原子云包含时我们突然关闭耦合场。所存储的信息在随后耦合激光开启时被读取出来。图2b给出了一结果图。虚线显示耦合激光在 $t=6.3 \mu\text{s}$ 时关闭，随后在44.3 μs 时开启。实心圆表示测得的探测强度。从这些数据中可以看出，当耦合激光再一次被开启时探测脉冲也再次产生，也就是说我们可以停止并控制探测脉冲的再生。类似的现象已经被近期的理论文章所预测^[12]。

[英文](#)

当探测脉冲被包含在介质中，激光场的相干信息已经被印记在原子上。当耦合激光关闭时，探测场被耗尽以保持暗态（等式（1）），而（可忽略的）原子振幅通过两光场间的受激光子交换从 $|1\rangle$ 态转移到 $|2\rangle$ 态。如上所述，由于被压缩的探测脉冲剩余的能量相当低，在原子布居振幅发生可观的改变之前，能量已经完全被耗尽。当耦合激光被重新开启时，逆过程发生，探测脉冲通过受激辐射到探测场而再生。随后探测脉冲在EIT条件下传播，就像耦合光束从未被关闭一样。 [英文](#)

在存储时间内，探测场的振幅信息包含在定义原子暗态的布居振幅之中。探测场的模式矢量信息包含在宏观样本中不同原子间的相对相位之中。冷原子的运用使热运动降至最低，也就使存储过程中相应的相对相位拖尾效应达到最小。（我们获得存储时间最长达到一个原子通过一个激光波长所需时间的50倍。通过等式（1）可以得出，两激光场波矢的差决定了印记在介质中的周期性相位图样的波长，该波长是单个激光波长的 10^5 倍。） [英文](#)

图2b中的再生探测脉冲与图2a中所示的“正常”EIT脉冲波形相同。图2c显示了光学相干信息在被耦合激光读取前，存储在原子介质中超过800 μs 的情况。这里的再生探测脉冲振幅与图2b相比有所降低。图2d为测量所得的一系列脉冲在原子云中的透射率与存储时间的函数关系图。

这些数据给出了 0.9 ms 的 $1/e$ 衰减时间，与计算所得的在密度为 $11 \text{ } \mu\text{m}^{-3}$ 的原子云中弹性碰撞的平均自由时间 0.5 ms 相当。关于退相干机制的进一步研究正在计划中，但不在本文讨论范围之内。 [英文](#)

我们已经在实验上验证了探测脉冲的再生是由于受激辐射而非自发辐射。为了实现这个目的，我们准备了所有原子处于 $|2\rangle$ 的态，随后单独开启耦合激光。耦合激光在几十个毫秒内被完全吸收，但没有在PMT上产生任何信号。 [英文](#)

图3a~3c显示了在相似条件下记录的三种PMT信号轨迹，不同之处在于我们改变了当耦合激光再次开启时的强度 I_{c2} 。当 I_{c2} 比最初的耦合强度 I_{c1} 大时，再生的探测脉冲振幅增大，其时间宽度减小（图3a）。对于 $I_{c2} < I_{c1}$ ，情况相反（图3c）。这些结果支持我们为整个过程建立的物理图像。存储的原子相干信息限定了耦合与再生探测场的拉比频率比率，以及再生脉冲的空间宽度。在图3d中，当 I_{c2} 很大时，再生的探测脉冲峰值强度超过初始输入脉冲的40%。 [英文](#)

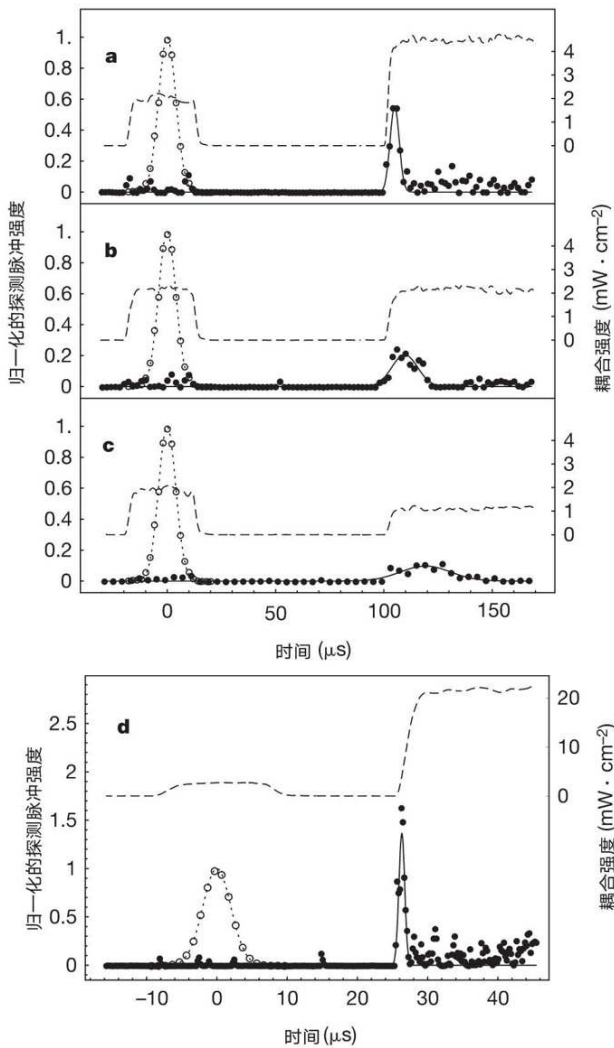


图3 . 不同的第二耦合脉冲强度 (I_{c2}) 下再生探测脉冲的测量。第一耦合脉冲强度 (I_{c1}) 保持恒定。a~c, 记录的是分别对应 I_{c2} / I_{c1} 之比为2, 1以及0.5的图形。一系列数据表明, 再生脉冲的高度、时间宽度的倒数均与 I_{c2} 成正比。观察到的现象与我们的物理图像相一致。由于原子相干限定了耦合和再生探测场的拉比频率之比 (等式 (1)), 再生探测脉冲的强度与耦合激光再次开启时的强度成正比。另外, 再生脉冲的空间宽度由原子相干的分布决定, 因此与最初被压缩的脉冲的空间范围相同。EIT条件下探测脉冲的群速度与耦合强度成正比^[4,7]。对于更大 (或更小) 的 I_{c2} , 再生探测脉冲获得了按比例更大 (或更小) 的群速度, 从而导致其时间宽度与 I_{c2} 成反比。图d显示再生的探测脉冲强度可以超过初始输入脉冲的强度, 图中所示情况超过了40%。(观察到的激光强度的峰-峰波动在10%以内。) 再生探测脉冲的能量在所有a~d图中相同, 这是由于在所有四种情况下, 处于量子态^[2]的原子 (可用于将光子激发到探测场中) 的总存储振幅相等。线和符号所对应的含义与图2一致。 英文

无耗散的脉冲存储和再生过程只有在耗散率和相干保持事件率之比

很小时才可能实现。当耦合场的增大或减小与探测脉冲的持续时间（ τ ）相比很迅速，而与 $1/\Gamma$ 相比变化缓慢时，这个比值等于（扎卡里·达顿和莱娜·韦斯特戈·豪，稿件准备中）

$$\frac{2\Gamma}{\Omega_c^2 + \Omega_p^2} \left(\frac{\dot{\Omega}_p}{\Omega_p} - \frac{\dot{\Omega}_c}{\Omega_c} \right) \quad (2)$$

这里 Γ 为态 $|3\rangle$ 的自发衰减率。我们的数值模拟显示，探测场一直通过使等式（2）的括号内项几乎相消的方式不断调节至与耦合场变化相匹配[13,14]。甚至对于关闭时间小于 $1/\Gamma$ 的情况，我们也可以证明，只要 $\tau \gg \Gamma/(\Omega_{c0}^2 + \Omega_{p0}^2)$ ，态 $|1\rangle$ 和 $|2\rangle$ 的相干就不存在衰减；这里 Ω_{c0} 和 Ω_{p0} 为在耦合激光关闭前的拉比频率。（文献12中提到的对于非耗散行为所必需的绝热要求太过严格。这个条件在低耦合激光电源开启和关闭时就不可避免地破坏。） [英文](#)

本文实验论证了相干光学信息可以被存储在原子介质中，并随后在磁阱捕获的冷原子云中利用EIT效应读取出来。本文通过实验验证了存储和读取过程是由两激光场之间的受激光子转移来控制的。应用一系列短耦合激光脉冲可以实现多重读取。图4a和4b显示了间隔高达几百个毫秒的二重和三重读取的测量结果。每个再生的探测脉冲包含“原子内存”的部分内容，而对于本实验所选择的参数，内存存在第二和第三个脉冲之后被耗尽。 [英文](#)

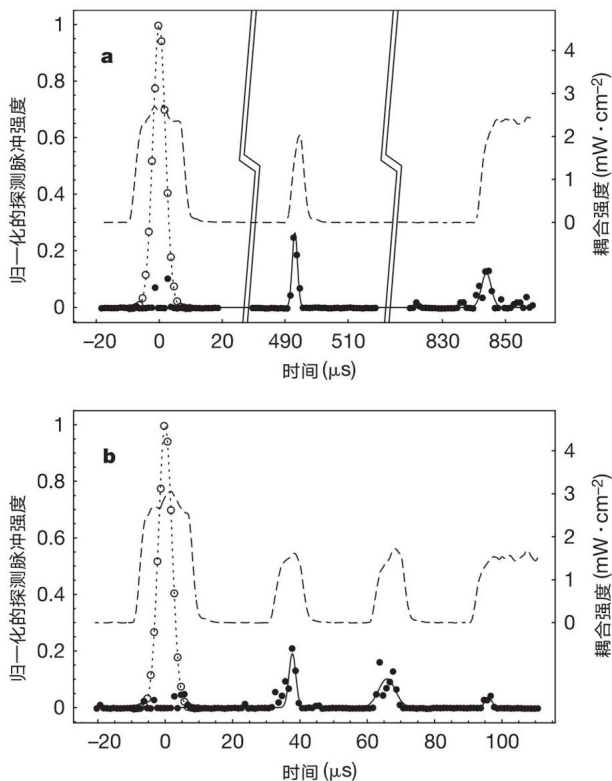


图4．原子内存的二重和三重读取测量。为了耗尽这些情况下的原子内存，我们使用了二重（a）和三重（b）短耦合脉冲。二（三）重再生探测脉冲的总能量与具有单一长耦合激光脉冲的单再生探测脉冲（图2和3中使用的脉冲）的能量相等。线和符号所对应的含义与图2一致。

英文

我们相信该系统可以应用于量子信息传递；例如，用于定态量子比特和飞行量子比特的互相转换^[15]。通过注入多重探测脉冲至玻色-爱因斯坦凝聚体（我们预计此条件下多数原子碰撞是可以相干保留的）并运用受控制的原子-原子之间的相互作用，量子信息处理在存储时间之内或许是可能的。

英文

（崔宁 翻译；石锦卫 审稿）

Experimental Violation of a Bell's Inequality with Efficient Detection

M. A. Rowe *et al.*

By the new millennium, careful tests of John Bell's celebrated "inequalities" had indicated that quantum physics seems to be inconsistent with any local realistic interpretation—that is, with a view in which systems have definite properties independent of other parts of the universe, and no influence can travel faster than light. But argument persisted due to various "loopholes" linked to experimental imperfections, including the limited efficiency of particle detectors. Here Mary Rowe and colleagues report violation of Bell's inequalities in experiments using heavy beryllium ions, for which they were able to detect all particles and thus close one loophole. Nonetheless, not all possible local realistic interpretations of quantum theory have been excluded even now. [中文](#)

Local realism is the idea that objects have definite properties whether or not they are measured, and that measurements of these properties are not affected by events taking place sufficiently far away¹. Einstein, Podolsky and Rosen² used these reasonable assumptions to conclude that quantum mechanics is incomplete. Starting in 1965, Bell and others constructed mathematical

inequalities whereby experimental tests could distinguish between quantum mechanics and local realistic theories^{1,3-5}. Many experiments^{1,6-15} have since been done that are consistent with quantum mechanics and inconsistent with local realism. But these conclusions remain the subject of considerable interest and debate, and experiments are still being refined to overcome “loopholes” that might allow a local realistic interpretation. Here we have measured correlations in the classical properties of massive entangled particles (⁹Be⁺ ions): these correlations violate a form of Bell’s inequality. Our measured value of the appropriate Bell’s “signal” is 2.25 ± 0.03 , whereas a value of 2 is the maximum allowed by local realistic theories of nature. In contrast to previous measurements with massive particles, this violation of Bell’s inequality was obtained by use of a complete set of measurements. Moreover, the high detection efficiency of our apparatus eliminates the so-called “detection” loophole. [中文](#)

EARLY experiments to test Bell’s inequalities were subject to two primary, although seemingly implausible, loopholes. The first might be termed the locality or “lightcone” loophole, in which the correlations of apparently separate events could result from unknown subluminal signals propagating between different regions of the apparatus. Aspect¹⁶ has given a brief history of this issue, starting with the experiments of ref. 8 and highlighting the strict relativistic separation between measurements reported by the Innsbruck group¹⁵. Similar results have also been reported for the Geneva experiment^{14,17}. The second loophole is usually referred to as the detection loophole. All experiments up to now have had detection efficiencies low enough to allow the possibility that the subensemble of detected events agrees with quantum mechanics even though the entire ensemble satisfies Bell’s inequalities. Therefore it must be assumed that the detected events represent the entire ensemble; a fair-

sampling hypothesis. Several proposals for closing this loophole have been made¹⁸⁻²⁴; we believe the experiment that we report here is the first to do so. Another feature of our experiment is that it uses massive particles. A previous test of Bell’s inequality was carried out on protons²⁵, but the interpretation of the detected events relied on quantum mechanics, as symmetries valid given quantum mechanics were used to extrapolate the data to a complete set of Bell’s angles. Here we do not make such assumptions. 中文

A Bell measurement of the type suggested by Clauser, Horne, Shimony and Holt⁵ (CHSH) consists of three basic ingredients (Fig. 1a). First is the preparation of a pair of particles in a repeatable starting configuration (the output of the “magic” box in Fig. 1a). Second, a variable classical manipulation is applied independently to each particle; these manipulations are labelled ϕ_1 and ϕ_2 . Finally, in the detection phase, a classical property with two possible outcomes is measured for each of the particles. The correlation of these outcomes

$$q(\phi_1, \phi_2) = \frac{\mathcal{N}_{\text{same}}(\phi_1, \phi_2) - \mathcal{N}_{\text{different}}(\phi_1, \phi_2)}{\mathcal{N}_{\text{same}} + \mathcal{N}_{\text{different}}} \quad (1)$$

is measured by repeating the experiment many times. Here $\mathcal{N}_{\text{same}}$ and $\mathcal{N}_{\text{different}}$ are the number of measurements where the two results were the same and different, respectively. The CHSH form of Bell’s inequalities states that the correlations resulting from local realistic theories must obey:

$$B(\alpha_1, \delta_1, \beta_2, \gamma_2) = |q(\delta_1, \gamma_2) - q(\alpha_1, \gamma_2)| + |q(\delta_1, \beta_2) + q(\alpha_1, \beta_2)| \leq 2 \quad (2)$$

where α_1 and δ_1 (β_2 and γ_2) are specific values of ϕ_1 (ϕ_2). For example, in a photon experiment¹⁵, parametric down-conversion prepares a pair of photons in a singlet Einstein–Podolsky–Rosen (EPR) pair. After this, a variable rotation of the photon polarization is applied to each photon. Finally, the photons’ polarization states, vertical or horizontal, are determined. 中文

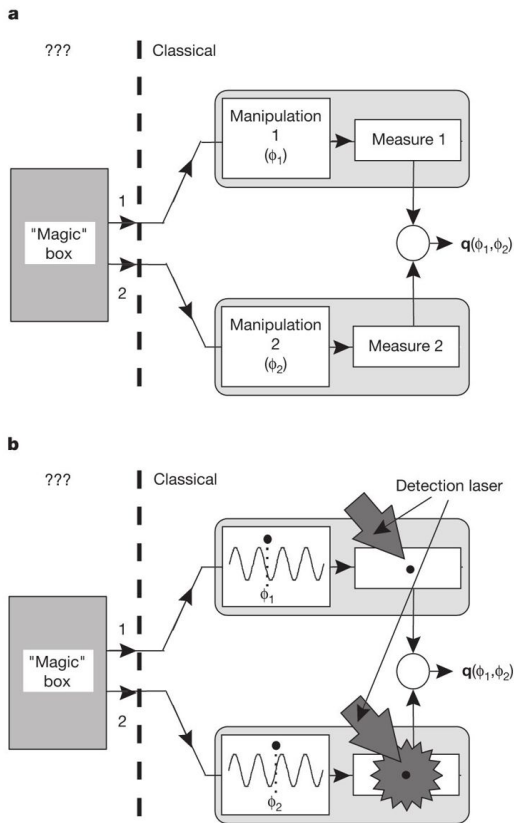


Fig. 1. Illustration of how Bell's inequality experiments work. The idea is that a "magic box" emits a pair of particles. We attempt to determine the joint properties of these particles by applying various classical manipulations to them and observing the correlations of the measurement outputs. **a**, A general CHSH type of Bell's inequality experiment. **b**, Our experiment. The manipulation is a laser wave applied with phases ϕ_1 and ϕ_2 to ion 1 and ion 2 respectively. The measurement is the detection of photons emanating from the ions upon application of a detection laser. Two possible measurement outcomes are possible, detection of few photons (as depicted for ion 1 in the figure) or the detection of many photons (as depicted for ion 2 in the figure). [中文](#)

Our experiment prepares a pair of two-level atomic ions in a repeatable configuration (entangled state). Next, a laser field is applied to the particles; the classical manipulation variables are the phases of this field at each ion's position. Finally, upon application of a detection laser beam, the classical property measured is the number of scattered photons emanating from the particles (which effectively measures their atomic states). Figure 1b shows how our experiment maps onto the general case. Entangled atoms produced in the context

of cavity-quantum-electrodynamics²⁶ could similarly be used to measure Bell's inequalities. [中文](#)

The experimental apparatus is as described in ref. 27. Two $^9\text{Be}^+$ ions are confined along the axis of a linear Paul trap with an axial centre-of-mass frequency of 5 MHz. We select two resolved levels of the $2S_{1/2}$ ground state, $|\downarrow\rangle \equiv |F=2, m_F=-2\rangle$ and $|\uparrow\rangle \equiv |F=1, m_F=-1\rangle$, where F and m_F are the quantum numbers of the total angular momentum. These states are coupled by a coherent stimulated Raman transition. The two laser beams used to drive the transition have a wavelength of 313 nm and a difference frequency near the hyperfine splitting of the states, $\omega_0 \approx 2\pi \times 1.25$ GHz. The beams are aligned perpendicular to each other, with their difference wavevector $\Delta\mathbf{k}$ along the trap axis. As described in ref. 27, it is possible in this configuration to produce the entangled state

$$|\psi_2\rangle = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle) \quad (3)$$

The fidelity $F = \langle\psi_2|\rho|\psi_2\rangle$, where ρ is the density matrix for the state we make, was about 88% for the data runs. In the discussion below we assume $|\psi_2\rangle$ as the starting condition for the experiment.

[中文](#)

After making the state $|\psi_2\rangle$, we again apply Raman beams for a pulse of short duration (~ 400 ns) so that the state of each ion j is transformed in the interaction picture as

$$|\uparrow_j\rangle \rightarrow \frac{1}{\sqrt{2}} (|\uparrow_j\rangle - ie^{i\phi}|\downarrow_j\rangle); |\downarrow_j\rangle \rightarrow \frac{1}{\sqrt{2}} (|\downarrow_j\rangle - ie^{i\phi}|\uparrow_j\rangle) \quad (4)$$

The phase, ϕ_j , is the phase of the field driving the Raman transitions (more specifically, the phase difference between the two Raman beams) at the position of ion j and corresponds to the inputs ϕ_1 and ϕ_2 in Fig. 1. We set this phase in two ways in the experiment. First, as an ion is moved along the trap axis this phase changes by $\Delta\mathbf{k} \cdot \Delta\mathbf{x}_j$. For

example, a translation of $\lambda/\sqrt{2}$ along the trap axis corresponds to a phase shift of 2π . In addition, the laser phase on both ions is changed by a common amount by varying the phase, ϕ_s , of the radio-frequency synthesizer that determines the Raman difference frequency. The phase on ion j is therefore

$$\phi_j = \phi_s + \Delta \mathbf{k} \cdot \mathbf{x}_j \tag{5}$$

In the experiment, the axial trap strength is changed so that the ions move about the centre of the trap symmetrically, giving $\Delta \mathbf{x}_1 = -\Delta \mathbf{x}_2$. Therefore the trap strength controls the differential phase, $\Delta \phi \equiv \phi_1 - \phi_2 = \Delta \mathbf{k} \cdot (\mathbf{x}_1 - \mathbf{x}_2)$, and the synthesizer controls the total phase, $\phi_{\text{tot}} \equiv \phi_1 + \phi_2 = 2\phi_s$. The calibration of these relations is discussed in the Methods. [中文](#)

The state of an ion, $|\downarrow\rangle$ or $|\uparrow\rangle$, is determined by probing the ion with circularly polarized light from a “detection” laser beam²⁷. During this detection pulse, ions in the $|\downarrow\rangle$ or bright state scatter many photons, and on average about 64 of these are detected with a photomultiplier tube, while ions in the $|\uparrow\rangle$ or dark state scatter very few photons. For two ions, three cases can occur: zero ions bright, one ion bright, or two ions bright. In the one-ion-bright case it is not necessary to know which ion is bright because the Bell’s measurement requires only knowledge of whether or not the ions’ states are different. Figure 2 shows histograms, each with 20,000 detection measurements. The three cases are distinguished from each other with simple discriminator levels in the number of photons collected with the phototube. [中文](#)

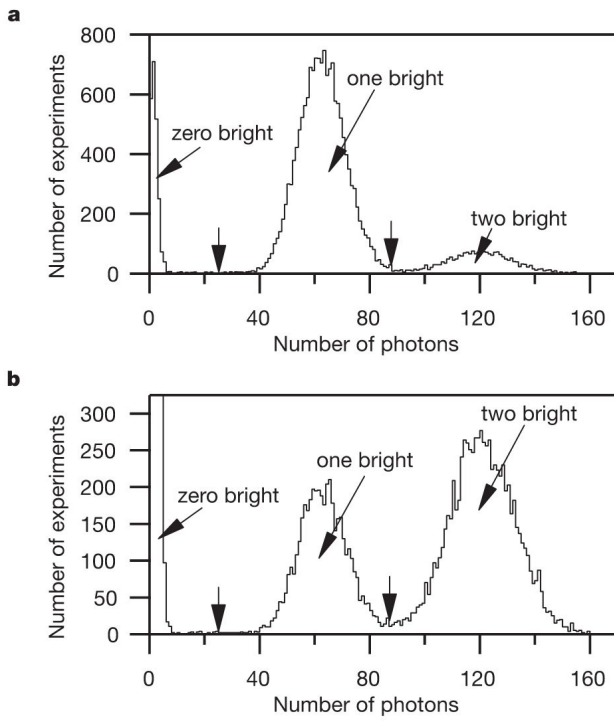


Fig. 2. Typical data histograms comprising the detection measurements of 20,000 experiments taking a total time of about 20 s. In each experiment the population in the $|\uparrow\rangle$ state is first coherently transferred to the $|F=1, M_F=+1\rangle$ to make it even less likely to fluoresce upon application of the detection laser. The detection laser is turned on and the number of fluorescence photons detected by the phototube in 1 ms is recorded. The cut between the one bright and two bright cases is made so that the fractions of two equal distributions which extend past the cut points are equal. The vertical arrows indicate the location of the cut between the 0 (1) bright and 1 (2) bright peaks at 25 (86) counts. **a**, Data histogram with a negative correlation using $\phi_1 = 3\pi/8$ and $\phi_2 = 3\pi/8$. For these data $N_0 \approx 2,200$, $N_1 \approx 15,500$ and $N_2 \approx 2,300$. **b**, Data histogram with a positive correlation using $\phi_1 = 3\pi/8$ and $\phi_2 = -\pi/8$. For these data $N_0 \approx 7,700$, $N_1 \approx 4,400$ and $N_2 \approx 7,900$. The zero bright peak extends vertically to 2,551. 中文

An alternative description of our experiment can be made in the language of spin-one-half magnetic moments in a magnetic field (directed in the $\hat{z}$ direction). The dynamics of the spin system are the same as for our two-level system²⁸. Combining the manipulation (equation (4)) and measurement steps, we effectively measure the spin projection of each ion j in the $\hat{r}_j$ direction, where the vector $\hat{r}_j$ is in the $\hat{x}$ - $\hat{y}$ plane at an angle ϕ_j to the $\hat{y}$ axis. Although we have used quantum-mechanical language to describe the manipulation and

measurement steps, we emphasize that both are procedures completely analogous to the classical rotations of wave-plates and measurements of polarization in an optical apparatus. [中文](#)

Here we calculate the quantum-mechanical prediction for the correlation function. Our manipulation step transforms the starting state, $|\psi_2\rangle$, to

$$|\psi_2'\rangle = \frac{1}{2\sqrt{2}} \left\{ (1 + e^{i(\phi_1 + \phi_2)}) (|\uparrow\uparrow\rangle - e^{-i(\phi_1 + \phi_2)} |\downarrow\downarrow\rangle) - i(1 - e^{i(\phi_1 + \phi_2)}) (e^{-i\phi_2} |\uparrow\downarrow\rangle + e^{-i\phi_1} |\downarrow\uparrow\rangle) \right\} \quad (6)$$

Using the measurement operators $\hat{\mathcal{N}}_{\text{different}} = \mathcal{N}_{\text{tot}} [|\uparrow\downarrow\rangle$ and $\hat{\mathcal{N}}_{\text{same}} = \mathcal{N}_{\text{tot}} [|\uparrow\uparrow\rangle \langle\uparrow\uparrow| + |\downarrow\downarrow\rangle \langle\downarrow\downarrow|]$, the correlation function is calculated to be

$$q(\phi_1, \phi_2) = \frac{1}{8} [2|1 + e^{i(\phi_1 + \phi_2)}|^2 - 2|1 - e^{i(\phi_1 + \phi_2)}|^2] = \cos(\phi_1 + \phi_2) \quad (7)$$

The CHSH inequality (equation (2)) is maximally violated by quantum mechanics at certain sets of phase angles. One such set is $\alpha_1 = -(\pi / 8)$, $\delta_1 = 3\pi / 8$, $\beta_2 = -(\pi / 8)$ and $\gamma_2 = 3\pi / 8$. With these phase angles quantum mechanics predicts

$$B\left(-\frac{\pi}{8}, \frac{3\pi}{8}, -\frac{\pi}{8}, \frac{3\pi}{8}\right) = 2\sqrt{2} \quad (8)$$

This violates the local realism condition, which requires that $B \leq 2$. [中文](#)

The correlation function is measured experimentally at four sets of phase angles, listed in Table 1. The experiment is repeated $N_{\text{tot}} = 20,000$ times at each of the four sets of phases. For each set of phases the correlation function is calculated using

$$q = \frac{(\mathcal{N}_0 + \mathcal{N}_2) - \mathcal{N}_1}{\mathcal{N}_{\text{tot}}} \quad (9)$$

Here N_0 , N_1 and N_2 are the number of events with zero, one and two ions bright, respectively. The correlation values from the four sets of phase angles are combined into the Bell's signal, $B(\alpha_1, \delta_1, \beta_2, \gamma_2)$, using equation (2). The correlation values and resulting Bell's signals from five data runs are given in Table 2. [中文](#)

Table 1. The four sets of phase angles used for the Bell's experiment

Experiment input	ϕ_1	ϕ_2	$\Delta\phi$	ϕ_{out}
α, β_2	$-\pi/8$	$-\pi/8$	0	$-\pi/4$
α, γ_2	$-\pi/8$	$3\pi/8$	$-\pi/2$	$+\pi/4$
δ, β_2	$3\pi/8$	$-\pi/8$	$+\pi/2$	$+\pi/4$
δ, γ_2	$3\pi/8$	$3\pi/8$	0	$+3\pi/4$

[中文](#)

Table 2. Correlation values and resulting Bell's signals for five experimental runs

Run number	$q(\alpha_1, \beta_2)$	$q(\alpha_1, \gamma_2)$	$q(\delta_1, \beta_2)$	$q(\delta_1, \gamma_2)$	$B(\alpha_1, \delta_1, \beta_2, \gamma_2)$
1	0.541	0.539	0.569	-0.573	2.222
2	0.575	0.570	0.530	-0.600	2.275
3	0.551	0.634	0.590	-0.487	2.262
4	0.575	0.561	0.559	-0.551	2.246
5	0.541	0.596	0.537	-0.571	2.245

The experimental angle values were $\alpha_1 = -(\pi / 8)$, $\delta_1 = 3\pi / 8$, $\beta_2 = -(\pi / 8)$, and $\gamma_2 = 3\pi / 8$. The statistical errors are 0.006 and 0.012 for the q and B values respectively. The systematic errors (see text) are 0.03 and 0.06 for the q and B values respectively. [中文](#)

So far we have described the experiment in terms of perfect implementation of the phase angles. In the actual experiment, however, α_1 , δ_1 , β_2 and γ_2 are not quite the same angles both times they occur in the Bell's inequality. In our experiment the dominant reason for this error results from the phase instability of the synthesizer, which can cause the angles to drift appreciably during four minutes, the time required to take a complete set of measurements. This random drift causes a root-mean-squared error for the correlation function of ± 0.03 on this timescale, which propagates to an error of ± 0.06 for the Bell's signal. The error for the Bell's signal from the five combined data sets is then ± 0.03 , consistent with

the run-to-run variation observed. Averaging the five Bell's signals from Table 2, we arrive at our experimental result, which is

$$B\left(-\frac{\pi}{8}, \frac{3\pi}{8}, -\frac{\pi}{8}, \frac{3\pi}{8}\right) = 2.25 \pm 0.03 \quad (10)$$

If we take into account the imperfections of our experiment (imperfect state fidelity, manipulations, and detection), this value agrees with the prediction of quantum mechanics. [中文](#)

The result above was obtained using the outcomes of every experiment, so that no fair-sampling hypothesis is required. In this case, the issue of detection efficiency is replaced by detection accuracy. The dominant cause of inaccuracy in our state detection comes from the bright state becoming dark because of optical pumping effects. For example, imperfect circular polarization of the detection light allows an ion in the $|\downarrow\rangle$ state to be pumped to $|\uparrow\rangle$, resulting in fewer collected photons from a bright ion. Because of such errors, a bright ion is misidentified 2% of the time as being dark. This imperfect detection accuracy decreases the magnitude of the measured correlations. We estimate that our Bell's signal would be 2.37 with perfect detection accuracy. [中文](#)

We have thus presented experimental results of a Bell's inequality measurement where a measurement outcome was recorded for every experiment. Our detection efficiency was high enough for a Bell's inequality to be violated without requiring the assumption of fair sampling, thereby closing the detection loophole in this experiment. The ions were separated by a distance large enough that no known interaction could affect the results; however, the lightcone loophole remains open here. Further details of this experiment will be published elsewhere. [中文](#)

Methods

Phase calibration

The experiment was run with specific phase differences of the Raman laser beam fields at each ion. In order to implement a complete set of laser phases, a calibration of the phase on each ion as a function of axial trap strength was made. We emphasize that the calibration method is classical in nature. Although quantum mechanics guided the choice of calibration method, no quantum mechanics was used to interpret the signal. General arguments are used to describe the signal resulting from a sequence of laser pulses and its dependence on the classical physical parameters of the system, the laser phase at the ion, and the ion's position. [中文](#)

In the calibration procedure, a Ramsey experiment was performed on two ions. The first $\pi / 2$ Rabi rotation was performed identically each time. The laser phases at the ions' positions for the second $\pi / 2$ Rabi rotation were varied, ϕ_1 for ion 1 and ϕ_2 for ion 2. The detection signal is the total number of photons counted during detection. With an auxiliary one-ion experiment we first established empirically that the individual signal depends only on the laser phase at an individual ion and is $C + A\cos\phi_j$. Here C and A are the offset and amplitude of the one-ion signal. We measure the detector to be linear, so that the detection signal is the sum of the two ions' individual signals. The two-ion signal is therefore

$$C + A\cos\phi_1 + C + A\cos\phi_2 = 2C + 2A\cos\left[\frac{1}{2}(\phi_1 + \phi_2)\right]\cos\left[\frac{1}{2}(\phi_1 - \phi_2)\right] \quad (11)$$

By measuring the fringe amplitude and phase as $\phi_s = (\phi_1 + \phi_2) / 2$ is swept, we calibrate $\phi_1 - \phi_2$ as a function of trap strength and ensure that $\phi_1 + \phi_2$ is independent of trap strength. [中文](#)

We use the phase convention that at the ion separation used for the entanglement preparation pulse the maximum of the correlation function is at $\phi_1 = \phi_2 = 0$ (or $\Delta\phi = \phi_{\text{tot}} = 0$). Our measurement

procedure begins by experimentally finding this condition of $\phi_1 = \phi_2 = 0$ by keeping $\Delta\phi = 0$ and scanning the synthesizer phase to find the maximum correlation. The experiment is then adjusted to the phase angles specified above by switching the axial trap strength to set $\Delta\phi$ and incrementing the synthesizer phase to set ϕ_{tot} . [中文](#)

Locality issues

The ions are separated by a distance of approximately $3\text{ }\mu\text{m}$, which is greater than 100 times the size of the wavepacket of each ion. Although the Coulomb interaction strongly couples the ions' motion, it does not affect the ions' internal states. At this distance, all known relevant interactions are expected to be small. For example, dipole-dipole interactions between the ions slightly modify the light-scattering intensity, but this effect is negligible for the ion-ion separations used²⁹. Also, the detection solid angle is large enough that Young's interference fringes, if present, are averaged out³⁰. Even though all known interactions would cause negligible correlations in the measurement outcomes, the ion separation is not large enough to eliminate the lightcone loophole. [中文](#)

We note that the experiment would be conceptually simpler if, after creating the entangled state, we separated the ions so that the input manipulations and measurements were done individually. However, unless we separated the ions by a distance large enough to overcome the lightcone loophole, this is only a matter of convenience of description and does not change the conclusions that can be drawn from the results. [中文](#)

(409, 791-794; 2001)

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References:

1. Clauser, J. F. & Shimony, A. Bell's theorem: experimental tests and implications. *Rep. Prog. Phys.* **41**, 1883-1927 (1978).
2. Einstein, A., Podolsky, B. & Rosen, N. Can quantum-mechanical description of reality be considered complete? *Phys. Rev.* **47**, 777-780 (1935).
3. Bell, J. S. On the Einstein-Podolsky-Rosen paradox. *Physics* **1**, 195-200 (1965).
4. Bell, J. S. in *Foundations of Quantum Mechanics* (ed. d'Espagnat, B.) 171-181 (Academic, New York, 1971).
5. Clauser, J. F., Horne, M. A., Shimony, A. & Holt, R. A. Proposed experiment to test local hidden-variable theories. *Phys. Rev. Lett.* **23**, 880-884 (1969).
6. Freedman, S. J. & Clauser, J. F. Experimental test of local hidden-variable theories. *Phys. Rev. Lett.* **28**, 938-941 (1972).
7. Fry, E. S. & Thompson, R. C. Experimental test of local hidden-variable theories. *Phys. Rev. Lett.* **37**, 465-468 (1976).
8. Aspect, A., Grangier, P. & Roger, G. Experimental realization of Einstein-Podolsky-Rosen-Bohm *Gedankenexperiment*: a new violation of Bell's inequalities. *Phys. Rev. Lett.* **49**, 91-94 (1982).
9. Aspect, A., Dalibard, J. & Roger, G. Experimental test of Bell's inequalities using time-varying analyzers. *Phys. Rev. Lett.* **49**, 1804-1807 (1982).
10. Ou, Z. Y. & Mandel, L. Violation of Bell's inequality and classical probability in a two-photon correlation experiment. *Phys. Rev. Lett.* **61**, 50-53 (1988).
11. Shih, Y. H. & Alley, C. O. New type of Einstein-Podolsky-Rosen-Bohm experiment using pairs of light quanta produced by optical parametric down conversion. *Phys. Rev. Lett.* **61**, 2921-2924 (1988).
12. Tapster, P. R., Rarity, J. G. & Owens, P. C. M. Violation of Bell's inequality over 4 km of optical fiber. *Phys. Rev. Lett.* **73**, 1923-1926 (1994).
13. Kwiat, P. G., Mattle, K., Weinfurter, H. & Zeilinger, A. New high-intensity source of polarization-entangled photon pairs. *Phys. Rev. Lett.* **75**, 4337-4341 (1995).
14. Tittel, W., Brendel, J., Zbinden, H. & Gisin, N. Violation of Bell inequalities by photons more than 10 km apart. *Phys. Rev. Lett.* **81**, 3563-3566 (1998).
15. Weihs, G. *et al.* Violation of Bell's inequality under strict Einstein locality conditions. *Phys. Rev. Lett.* **81**, 5039-5043 (1998).
16. Aspect, A. Bell's inequality test: more ideal than ever. *Nature* **398**, 189-190 (1999).
17. Gisin, N. & Zbinden, H. Bell inequality and the locality loophole: active versus passive switches. *Phys. Lett. A* **264**, 103-107 (1999).
18. Lo, T. K. & Shimony, A. Proposed molecular test of local hidden-variable theories. *Phys. Rev. A* **23**, 3003-3012 (1981).
19. Kwiat, P. G., Eberhard, P. H., Steinberg, A. M. & Chiao, R. Y. Proposal for a loophole-free Bell inequality experiment. *Phys. Rev. A* **49**, 3209-3220 (1994).
20. Huelga, S. F., Ferrero, M. & Santos, E. Loophole-free test of the Bell inequality. *Phys. Rev. A* **51**, 5008-5011 (1995).

21. Fry, E. S., Walther, T. & Li, S. Proposal for a loophole free test of the Bell inequalities. *Phys. Rev. A* **52**, 4381-4395 (1995).
22. Freyberger, M., Aravind, P. K., Horne, M. A. & Shimony, A. Proposed test of Bell's inequality without a detection loophole by using entangled Rydberg atoms. *Phys. Rev. A* **53**, 1232-1244 (1996).
23. Brif, C. & Mann, A. Testing Bell's inequality with two-level atoms via population spectroscopy. *Europhys. Lett.* **49**, 1-7 (2000).
24. Beige, A., Munro, W. J. & Knight, P. L. A Bell's inequality test with entangled atoms. *Phys. Rev. A* **62**, 052102-1-052102-9 (2000).
25. Lamehi-Rachti, M. & Mittag, W. Quantum mechanics and hidden variables: a test of Bell's inequality by the measurement of the spin correlation in low-energy proton-proton scattering. *Phys. Rev. D* **14**, 2543-2555 (1976).
26. Hagley, E. *et al.* Generation of Einstein-Podolsky-Rosen pairs of atoms. *Phys. Rev. Lett.* **79**, 1-5 (1997).
27. Sackett, C. A. *et al.* Experimental entanglement of four particles. *Nature* **404**, 256-259 (2000).
28. Feynman, R. P., Vernon, F. L. & Hellwarth, R. W. Geometrical representation of the Schrödinger equation for solving maser problems. *J. Appl. Phys.* **28**, 49-52 (1957).
29. Richter, T. Cooperative resonance fluorescence from two atoms experiencing different driving fields. *Optica Acta* **30**, 1769-1780 (1983).
30. Eichmann, U. *et al.* Young's interference experiment with light scattered from two atoms. *Phys. Rev. Lett.* **70**, 2359-2362 (1993).

Acknowledgements. We thank A. Ben-Kish, J. Bollinger, J. Britton, N. Gisin, P. Knight, P. Kwiat and I. Percival for useful discussions and comments on the manuscript. This work was supported by the US National Security Agency (NSA) and the Advanced Research and Development Activity (ARDA), the US Office of Naval Research, and the US Army Research Office. This paper is a contribution of the National Institute of Standards and Technology and is not subject to US copyright.

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利用高效检测来实验验证贝尔不等式的违背

罗等

新的千年到来之前，对约翰·贝尔著名的“不等式”进行的种种仔细的实验验证表明量子物理学似乎与任何定域实在论的解释都不相吻合，定域实在论认为系统有确定的性质，与世界的其他事物无关，且任何影响都不能超光速传播。但由于存在与实验不完美有关的各种各样的、包括粒子探测器的有效探测效率在内的“漏洞”，争论一直持续存在。本文中，玛丽·罗和其同事们报道了利用重铍离子所做的实验中贝尔不等式的违背。由于他们在实验中可以探测到所有的粒子，从而堵上了一个漏洞。然而，即使是现在，仍不能排除对量子理论的所有可能的定域实在论的解释。

[英文](#)

定域实在论的观点认为，无论是否被测量，物体都具有确定的性质，对这些性质的测量并不受足够远发生的事件的影响^[1]。爱因斯坦-波多尔斯基-罗森^[2]用这些合理的假设，得出量子力学是不完备的结论。从1965年开始，贝尔和其他人构建了一个数学不等式，依靠实验验证能区分子量子力学与定域实在论的理论^[1,3-5]。已进行的很多实验^[1,6-15]与量子力学理论相符，而与定域实在论不符。但这些结论仍然是大家相当感兴趣和有争议的问题，一些实验仍在不断完善以克服那些允许定域实在论解释的“漏洞”。我们现已测量了大质量的纠缠粒子（ $^9\text{Be}^+$ 离子）在经典性质下的关联：这些关联违反了贝尔不等式的形式。我们得到的贝尔“信号”测量值是 2.25 ± 0.03 ，然而2是自然界定域实在论所允许的最大值。与过去的重粒子测量相比，这次背离贝尔不等式的结果是使用一组完备测量得出的。此外，我们装置的高检测效率消除了所谓的“检测”漏洞。

[英文](#)

验证贝尔不等式的早期实验受限于两个似乎令人难以置信的初级漏洞。第一个漏洞可称为定域性的，或“光锥”漏洞，这个漏洞指的是两个明显分离的事件之间的关联有可能是某些未知的亚光速信号在装置的不同区域之间传播造成的。阿斯佩^[16]给出了这个问题的简明综述，综述从文献8的实验开始，并着重介绍了由因斯布鲁克小组^[15]报道的测量之间严格的相对论性分离。日内瓦实验^[14,17]也报道了类似的结果。第二个漏洞通常被认为是检测漏洞。至今的所有实验检测的效率很低，以至于允许存在即使整个系综满足贝尔不等式，而检测事件的子系综与量子力学符合的可能性。因此，必须假设检测的事件代表整个系综；这是一个合理的取样假设。现已提出了堵上这个漏洞的数个建议^[18-24]；我们相信，本文所述乃是首次针对堵上此漏洞所进行的实验。我们实验的另一个特点是采用大质量粒子。之前的贝尔不等式验证是利用质子进行的^[25]，但检测事件的解释依据是量子力学，如量子力学中给出的对称性被用于将数据外推到贝尔角的完备集。此处我们并未采用这些假设。

英文

由克劳塞、霍恩、希莫尼和霍尔特^[5]（CHSH）提出的这类贝尔测量包括三个基本部分（图1a）。第一部分是制备在可重复的起始组态中的一对粒子（图1a中“魔盒”的输出）。第二部分是对每个粒子独立地用一个可变的经典操控，这些操控标记为 ϕ_1 和 ϕ_2 ；最后在检测阶段，对每个粒子的经典性质进行测量，皆有两个可能的结果。这些结果的关联函数为

$$q(\phi_1, \phi_2) = \frac{N_{\text{same}}(\phi_1, \phi_2) - N_{\text{different}}(\phi_1, \phi_2)}{N_{\text{same}} + N_{\text{different}}} \quad (1)$$

式（1）是多次重复实验的测量结果。式中 N_{same} 和 $N_{\text{different}}$ 分别是两个结果相同和不同时的测量数目。贝尔不等式的CHSH形式表述为，由定域实在论得出的相关性必须遵从下式：

$$B(\alpha_1, \delta_1, \beta_2, \gamma_2) = |q(\delta_1, \gamma_2) - q(\alpha_1, \gamma_2)| + |q(\delta_1, \beta_2) + q(\alpha_1, \beta_2)| \leq 2 \quad (2)$$

式中 α_1 和 δ_1 （ β_2 和 γ_2 ）是 ϕ_1 （ ϕ_2 ）的特定值。例如，在光子实验中^[15]，利用参数下转换技术把一对光子制备在爱因斯坦-波多尔斯基-罗森（EPR）单重态上，然后让每个光子通过一个角度可变的偏振片。最

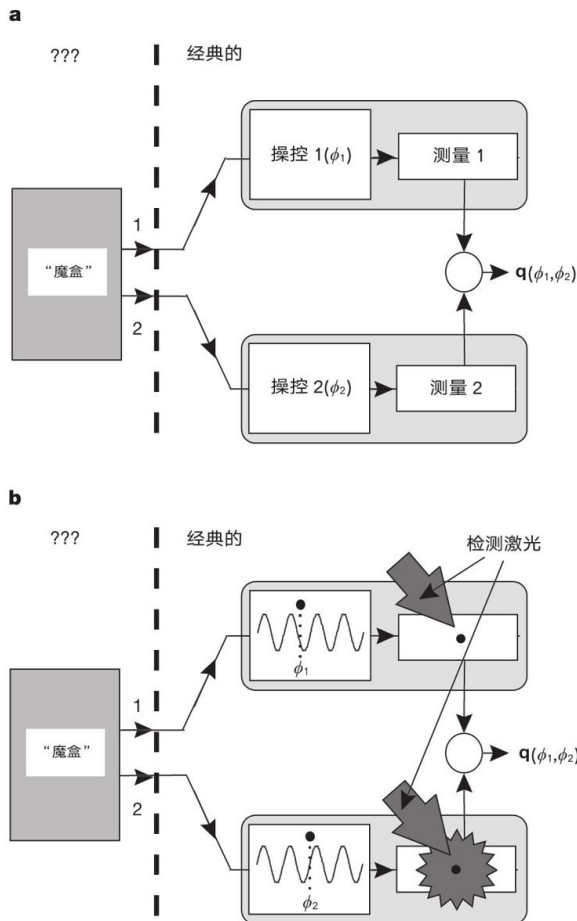


图1．贝尔不等式验证实验如何开展的示意图。实验思想是一个“魔盒”发射一对粒子。通过应用各种经典的操控方法，我们试图测定这些粒子的联合性质，并观测其测量输出的关联。**a**，一般的CHSH型贝尔不等式实验；**b**，我们的实验。操控是用相位为 ϕ_1 和 ϕ_2 的激光波分别加到离子1和2上。测量是对离子施加探测激光后，检测从离子发射出来的光子。有两个可能的测量结果，几乎检测不到光子（如图中对离子1的描绘）或检测到许多光子（如图中对离子2的描绘）。

英文

实验中我们把一对二能级原子离子制备在可重复组态（纠缠态）上。其次，在粒子上加一激光场；经典操控的变量是每个离子所在处这个场的相位。最后，应用检测激光束之后，被测的经典性质是从粒子发射出的散射光子的数量（通过它可有效地测量粒子的原子态）。图1b展示了我们的实验与一般实验的对应。在腔量子电动力学意义下产生的纠缠的原子^[26]能类似地用于测量贝尔不等式。

英文

实验装置如文献27中所描述。两个 $^9\text{Be}^+$ 离子以5 MHz的轴向质心频率约束在沿着线性保罗阱的轴上。我们选择 $2S_{1/2}$ 基态的两个可分辨的能级， $|\downarrow\rangle \equiv |F=2, m_F=-2\rangle$ 和 $|\uparrow\rangle \equiv |F=1, m_F=-1\rangle$ ，式中 F 和 m_F 是总角动量的量子数。这些态经由相干受激拉曼跃迁耦合。用于驱动跃迁的两束激光波长为313 nm，两者的差频接近态的超精细分裂 $\omega_0 \approx 2\pi \times 1.25$ GHz的跃迁。两束激光彼此相互垂直，其波矢差 $\Delta\mathbf{k}$ 沿着阱的轴。如文献27中所述，在这种组态中可能产生纠缠态

$$|\psi_2\rangle = \frac{1}{\sqrt{2}} (|\uparrow\uparrow\rangle - |\downarrow\downarrow\rangle) \quad (3)$$

对于运行数据，保真度 $F = \langle \psi_2 | \rho | \psi_2 \rangle$ 约为88%，式中 ρ 是我们所产生的态的密度矩阵。在以下讨论中，我们假定 $|\psi_2\rangle$ 是实验的起始条件。

英文

在产生了态 $|\psi_2\rangle$ 后，我们再应用拉曼光束作为一个短脉冲（约400 ns），因此每个离子 j 的态在相互作用绘景中转变为

$$|\uparrow_j\rangle \rightarrow \frac{1}{\sqrt{2}} (|\uparrow_j\rangle - ie^{-i\phi_j} |\downarrow_j\rangle); |\downarrow_j\rangle \rightarrow \frac{1}{\sqrt{2}} (|\downarrow_j\rangle - ie^{i\phi_j} |\uparrow_j\rangle) \quad (4)$$

相位 ϕ_j 是在离子 j 的位置上驱动拉曼跃迁的场的相位（更明确地说，是两束拉曼光束之间的相位差），对应于图1中的输入 ϕ_1 和 ϕ_2 。我们在实验中按两种方式设定其相位。首先，在离子沿着阱轴运动时，相位变化为 $\Delta\mathbf{k} \cdot \Delta\mathbf{x}_{j0}$ 。例如，沿着阱轴的平移 $\lambda/\sqrt{2}$ ，相当于 2π 的相移。此外，改变决定拉曼差频的射频合成器的相位 ϕ_s ，使加在两个离子上的激光相位发生同量的变化。从而离子 j 的相位是

$$\phi_j = \phi_s + \Delta\mathbf{k} \cdot \mathbf{x}_j \quad (5)$$

在实验中，轴向阱的强度改变，因此离子绕阱的中心对称地运动，给出 $\Delta\mathbf{x}_1 = -\Delta\mathbf{x}_2$ 。因此阱的强度控制了相位差值， $\Delta\phi \equiv \phi_1 - \phi_2 = \Delta\mathbf{k} \cdot (\mathbf{x}_1 - \mathbf{x}_2)$ ，合成器控制了总相位 $\phi_{\text{tot}} \equiv \phi_1 + \phi_2 = 2\phi_s$ 。这些关系的标定在方法一节中进行讨论。

英文

一个离子的态， $|\downarrow\rangle$ 或 $|\uparrow\rangle$ ，用“检测”激光束中的圆偏振光探测离子来确定^[27]。在检测脉冲持续时间内，处于 $|\downarrow\rangle$ 态或明态的离子散射许多

光子，用光电倍增管检测到平均约64个，处于 $|\uparrow\rangle$ 态或暗态的离子散射很少的光子。对两个离子而言可能出现三种情况：无离子处于明态，一个离子处于明态，两个离子处于明态。在一个离子处于明态的情况下，不必知道是哪一个离子，因为贝尔的测量仅要求知道离子态是否不同。图2示出了直方图，每个实验重复测量20,000次。用光电管收集到的光子进行计数即可区分这三种情况。

英文

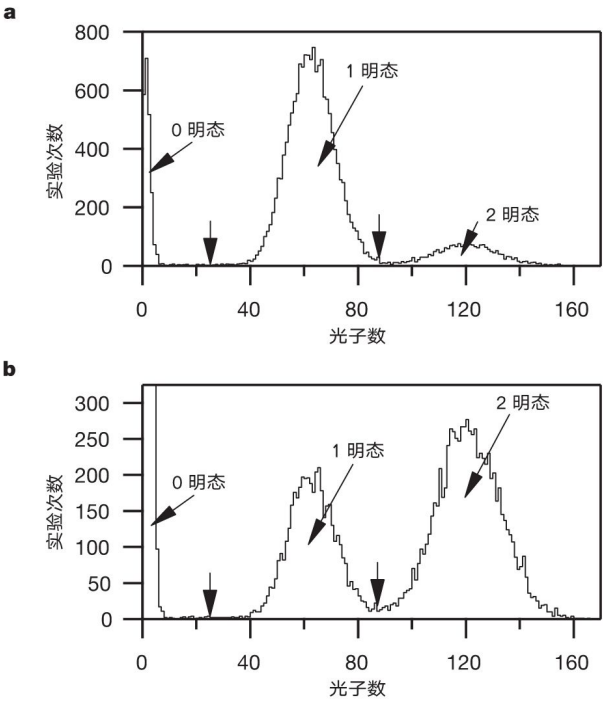


图2．包含20,000次实验的检测结果的典型数据直方图，所用的总时间约为20 s。在每次实验中，在 $|\uparrow\rangle$ 态的粒子数，首先相干转移到 $|F = 1, M_F = +1\rangle$ ，使得它在检测激光作用下也不发出荧光。打开检测激光，光电管在1 ms内记录检测到的荧光光子数。在一个离子处于明态和两个离子处于明态的情况之间进行截断，使两个相等分布扩展到截断点以外的部分所占的比例相等。垂直的箭头表示在25（86）计数时，在0（1）个离子处于明态与1（2）个离子处于明态峰值之间的截断。**a.** 用 $\phi_1 = 3\pi/8$ 和 $\phi_2 = 3\pi/8$ 的负相关数据直方图。对于这些数据， $N_0 \approx 2,200$ ， $N_1 \approx 15,500$ 和 $N_2 \approx 2,300$ 。**b.** 用 $\phi_1 = 3\pi/8$ 和 $\phi_2 = -\pi/8$ 的正相关数据直方图。对于这些数据， $N_0 \approx 7,700$ ， $N_1 \approx 4,400$ 和 $N_2 \approx 7,900$ 。无离子处于明态的峰值将垂直扩展到2,551。

英文

我们的实验还能用磁场中（在 $\hat{z}$ 方向上）1/2自旋磁矩的语言这另一种方式进行描述。自旋系统的动力学与我们的二能级系统是相同的[28]。结合操控（式（4））和测量步骤，我们有效地测量了每个离子j在

$\hat{j}$ 方向上的自旋投影，其中矢量 $\hat{j}$ 在 $\hat{x}-\hat{y}$ 平面上与 $\hat{y}$ 呈角度 ϕ_j 。虽然，我们已经使用量子力学的语言来描述操控和测量步骤，我们强调两者是与光学装置中波片的经典旋转和偏振的测量完全类似的步骤。 [英文](#)

这里，我们计算了关联函数的量子力学预测结果。我们的操控步骤将起始态 $|\psi_2\rangle$ 变换为

$$|\psi_2\rangle = \frac{1}{2\sqrt{2}} \left\{ (1 + e^{i(\phi_1 + \phi_2)}) (|\uparrow\uparrow\rangle - e^{-i(\phi_1 + \phi_2)} |\downarrow\downarrow\rangle) - i(1 - e^{i(\phi_1 + \phi_2)}) (e^{-i\phi_2} |\uparrow\downarrow\rangle + e^{-i\phi_1} |\downarrow\uparrow\rangle) \right\} \quad (6)$$

应用测量算符 $\hat{N}_{\text{different}} = N_{\text{tot}} [|\uparrow\downarrow\rangle\langle\uparrow\downarrow|]$ 和 $\hat{N}_{\text{same}} = N_{\text{tot}} [|\uparrow\uparrow\rangle\langle\uparrow\uparrow| + |\downarrow\downarrow\rangle\langle\downarrow\downarrow|]$ ，计算的关联函数为

$$q(\phi_1, \phi_2) = \frac{1}{8} [2|1 + e^{i(\phi_1 + \phi_2)}|^2 - 2|1 - e^{i(\phi_1 + \phi_2)}|^2] = \cos(\phi_1 + \phi_2) \quad (7)$$

根据量子力学，CHSH不等式（式（2））在特定相角组合处达到了最大的背离。一组这样的组合为 $\alpha_1 = -(\pi / 8)$ ， $\delta_1 = 3\pi / 8$ ， $\beta_2 = -(\pi / 8)$ 及 $\gamma_2 = 3\pi / 8$ 。用这些相角，量子力学预测

$$B\left(-\frac{\pi}{8}, \frac{3\pi}{8}, -\frac{\pi}{8}, \frac{3\pi}{8}\right) = 2\sqrt{2} \quad (8)$$

这背离了要求 $B \leq 2$ 的定域实在论条件。 [英文](#)

实验上用列于表1的四组相角测量关联函数。四组相角的每一组，实验都重复 $N_{\text{tot}} = 20,000$ 次。对每组相位，用下式计算关联函数

$$q = \frac{(N_0 + N_2) - N_1}{N_{\text{tot}}} \quad (9)$$

式中 N_0 ， N_1 ， N_2 分别是以0，1和2个离子处于明态的事件数目。四组相角的相关值已用式（2）代入贝尔信号 $B(\alpha_1, \delta_1, \beta_2, \gamma_2)$ 中。表2给出了五次数据运行的相关值和得出的贝尔信号。 [英文](#)

表1. 用于贝尔实验的四组相角

实验输入	ϕ_1	ϕ_2	$\Delta\phi$	ϕ_{out}
$\alpha_1 \beta_2$	$-\pi/8$	$-\pi/8$	0	$-\pi/4$
$\alpha_1 \gamma_2$	$-\pi/8$	$3\pi/8$	$-\pi/2$	$+\pi/4$
$\delta_1 \beta_2$	$3\pi/8$	$-\pi/8$	$+\pi/2$	$+\pi/4$
$\delta_1 \gamma_2$	$3\pi/8$	$3\pi/8$	0	$+3\pi/4$

英文

表2. 五次实验运行的相关值和得出的贝尔信号

运行序号	$q(\alpha_i, \beta_j)$	$q(\alpha_i, \gamma_j)$	$q(\delta_i, \beta_j)$	$q(\delta_i, \gamma_j)$	$B(\alpha_i, \delta_i, \beta_j, \gamma_j)$
1	0.541	0.539	0.569	-0.573	2.222
2	0.575	0.570	0.530	-0.600	2.275
3	0.551	0.634	0.590	-0.487	2.262
4	0.575	0.561	0.559	-0.551	2.246
5	0.541	0.596	0.537	-0.571	2.245

实验的角度数值是 $\alpha_1 = -(\pi / 8)$, $\delta_1 = 3\pi / 8$, $\beta_2 = -(\pi / 8)$ 及 $\gamma_2 = 3\pi / 8$ 。对 q 和 B 的统计误差分别为0.006和0.012。对 q 和 B 的系统误差（见正文）分别为0.03和0.06。[英文](#)

在此为止，我们已用理想的相角设定描述了实验。然而，在实际实验中，两次代入贝尔不等式的角 α_1 、 δ_1 、 β_2 和 γ_2 并不是完全相同的。在我们的实验中，这个误差主要来自合成器的相位不稳定性，使相角在四分钟内产生了明显的漂移，这正是一整套测量所需要的时间。这项随机漂移对于关联函数来说，在这一时标上产生了 ± 0.03 的方均根误差，它传递到贝尔信号的误差为 ± 0.06 。来自五个数据组的贝尔信号的误差则为 ± 0.03 ，与观测到的每次运行变化是相符的。对表2中五个贝尔信号求平均，我们得到的实验结果为

$$B\left(-\frac{\pi}{8}, \frac{3\pi}{8}, -\frac{\pi}{8}, \frac{3\pi}{8}\right) = 2.25 \pm 0.03$$

(10)

如果考虑到我们实验中的不完美的方面（不完美的态保真度、操控和检测），这个结果与量子力学的预测值是一致的。[英文](#)

上述结果是利用每个实验的输出量得出的，因此不要求有合理取样的前提。在这种情况下，检测效率的问题由检测准确度代替。在我们实验中，态检测的不准确的主要原因来自光抽运效应引起的明态变为暗态。例如，检测光不完美的圆偏振允许离子由 $|\downarrow\rangle$ 态抽运到 $|\uparrow\rangle$ ，从而处于明态的离子收集到较少的光子。由于这类误差的存在，一个离子处于

明态而被错判为处于暗态的概率是2%。这类不完美的检测准确度降低了测量相关性的量级。我们估计本文贝尔信号在完美检测准确度下将是2.37。 [英文](#)

我们已经给出了每次实验记录的贝尔不等式测量的实验结果。我们的检测效率高到足以不要求有合理取样的前提也可以给出贝尔不等式背离的结论，从而在这个实验中堵上了检测漏洞这个问题。离子之间相距很远，远到没有已知的相互作用可以影响实验结果；但是，本文还没有解决光锥漏洞的问题。这个实验的更多细节将发表在其他地方。 [英文](#)

方法

相位标定

实验是在每个离子的拉曼激光光束场的特定相位差下运行的。为了实现激光相位的完备集，每个离子上的激光相位被标定为轴向阱强度的函数。我们强调标定方法本质上是经典的。虽然，量子力学影响了标定方法的选择，但并没有使用量子力学来解释信号。一般的理论用于描述从一系列激光脉冲得出的信号，以及它与系统的经典物理参量的相关关系，经典的物理参量包括离子上的激光相位和离子的位置。 [英文](#)

在标定过程中，对两个离子进行了拉姆齐实验。每次实验中第一个 $\pi/2$ 的拉比旋转都相同。对于第二个 $\pi/2$ 拉比旋转，离子处的激光相位发生了改变，离子1处为 ϕ_1 ，离子2处为 ϕ_2 。检测信号是在检测期间记录的总光子数。用一个辅助的单离子实验，我们首先在实践经验上确立了单个信号仅与单个离子处的激光相位有关，信号记为 $C + A \cos \phi_j$ 。此处的 C 和 A 是单离子信号的偏置和振幅。我们测得检测器是线性的，因此检测信号是两个离子的单独信号之和。从而两个离子的信号为

$$C + A \cos \phi_1 + C + A \cos \phi_2 = 2C + 2A \cos \left[\frac{1}{2} (\phi_1 + \phi_2) \right] \cos \left[\frac{1}{2} (\phi_1 - \phi_2) \right] \quad (11)$$

当扫描 $\phi_s = (\phi_1 + \phi_2)/2$ 时，通过测量条纹振幅和相位，我们标定了 $\phi_1 - \phi_2$ 作为阱强度的函数，并确保 $\phi_1 + \phi_2$ 与阱强度无关。 [英文](#)

我们按照惯例，在用于纠缠制备脉冲的离子分离处，关联函数在 $\phi_1 = \phi_2 = 0$ （或 $\Delta\phi = \phi_{\text{tot}} = 0$ ）处取得最大值。在测量的开始，我们通过保持 $\Delta\phi = 0$ ，进而用实验方法找到 $\phi_1 = \phi_2 = 0$ 的条件，并扫描合成器的相位来找到关联函数最大值。然后在实验中通过调整轴阱强度来设置 $\Delta\phi$ ，通过增加合成器相位来设置 ϕ_{tot} ，把相角调整到上文给出的相应值。 [英文](#)

定域性的争论

离子间相隔的距离约为 $3\ \mu\text{m}$ ，这是每个离子的波包尺寸的100倍。虽然，库仑相互作用与离子的运动发生强烈的耦合，但它并不影响离子的内部状态。在这个距离上，所有已知的相互作用的预期都是很小的。例如，在离子之间的偶极-偶极相互作用稍微改变了光散射强度，但这种影响对于所用的离子之间的距离来说是可以忽略不计的^[29]。同时，检测立体角大到足以使杨氏干涉条纹（如存在）被平均掉^[30]。即使所有已知的相互作用在测量结果中的相关性可以忽略不计，但离子之间的距离仍不会大到足以消除光锥漏洞。 [英文](#)

我们注意到，如果在建立纠缠态后分开离子，使输入操控和测量分别进行，实验将在概念上更为简单。然而，除非我们把离子之间的距离扩大到足以克服光锥漏洞，否则，这只是描述方便与否的问题，而并不会改变从实验结果所得出的结论。 [英文](#)

（沈乃澂 翻译；李军刚 审稿）

Superconductivity at 39 K in Magnesium Diboride

J. Nagamatsu *et al.*

By 2001, a variety of materials based on copper oxides that superconduct at temperatures over 130 K had been observed. Here physicist Jun Nagamatsu and colleagues reported their observation of superconductivity at a temperature of “just” 39 K, but in a very different material: the metallic compound magnesium diboride. This work established a new record for the superconducting transition temperature in metallic compounds, for which the previous high had been, since 1973, only 23 K. Later work would show that the behaviour of this compound fits the standard Bardeen–Cooper–Schrieffer theory of superconductivity, although with some peculiarities. Due to the low cost of its constituent elements and fabrication, magnesium diboride has become a widely used superconductor for practical applications. [中文](#)

In the light of the tremendous progress that has been made in raising the transition temperature of the copper oxide superconductors (for a review, see ref. 1), it is natural to wonder how high the transition temperature, T_c , can be pushed in other classes of materials. At present, the highest reported values of T_c for non-copper-oxide bulk superconductivity are 33 K in electron-doped $\text{Cs}_x\text{Rb}_y\text{C}_{60}$ (ref. 2), and 30 K in $\text{Ba}_{1-x}\text{K}_x\text{BiO}_3$ (ref. 3). (Hole-doped C_{60} was recently found⁴ to be superconducting with a T_c as high as 52

K, although the nature of the experiment meant that the supercurrents were confined to the surface of the C_{60} crystal, rather than probing the bulk.) Here we report the discovery of bulk superconductivity in magnesium diboride, MgB_2 . Magnetization and resistivity measurements establish a transition temperature of 39 K, which we believe to be the highest yet determined for a non-copper-oxide bulk superconductor. [中文](#)

THE samples were prepared from powdered magnesium (Mg; 99.9%) and powdered amorphous boron (B; 99%) in a dry box. The powders were mixed in an appropriate ratio (Mg:B=1:2), ground and pressed into pellets. The pellets were heated at 973 K under a high argon pressure, 196 MPa, using a hot isostatic pressing (HIP) furnace (O₂Dr.HIP, Kobelco) for 10 hours. Powder X-ray diffraction was performed by a conventional X-ray spectrometer with a graphite monochromator (RINT-2000, Rigaku). Intensity data were collected with $CuK\alpha$ radiation over a 2θ range from 5° to 80° at a step width of 0.02° . [中文](#)

Figure 1 shows a typical X-ray diffraction pattern of MgB_2 taken at room temperature. All the intense peaks can be indexed assuming a hexagonal unit cell, with $a=3.086 \text{ \AA}$ and $c=3.524 \text{ \AA}$. Figure 2 shows the crystal structure of MgB_2 (ref. 5), of which the space group is $P6 / mmm$ (no.191). As shown in Fig. 2, the boron atoms are arranged in layers, with layers of Mg interleaved between them. The structure of each boron layer is the same as that of a layer in the graphite structure: each boron atom is here equidistant from three other boron atoms. Therefore, MgB_2 is composed of two layers of boron and magnesium along the c axis in the hexagonal lattice. [中文](#)

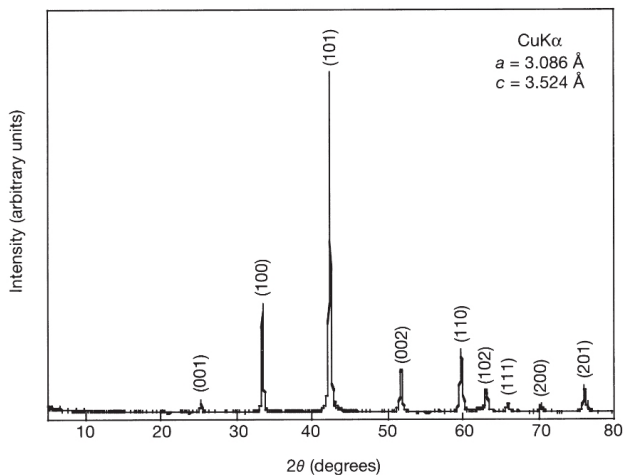


Fig. 1. X-ray diffraction pattern of MgB_2 at room temperature.

中文

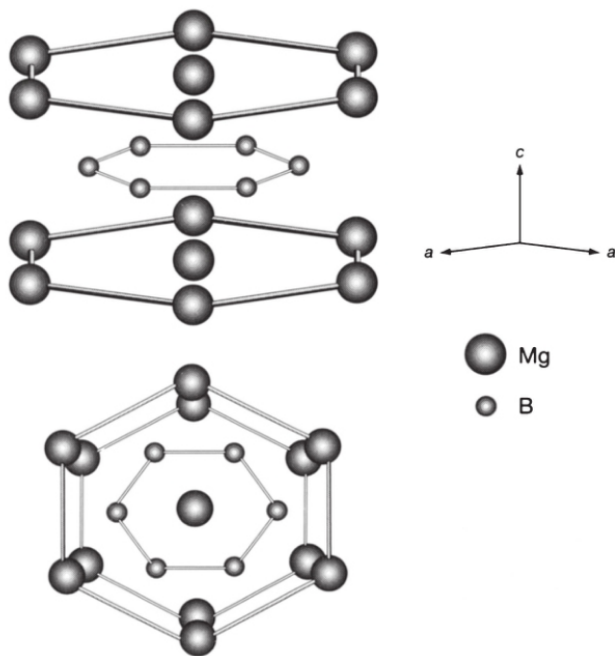


Fig. 2. Crystal structure of MgB_2 .

中文

Magnetization measurements were also performed with a SQUID magnetometer (MPMSR2, Quantum Design). Figure 3 shows the magnetic susceptibility ($\chi = M / H$, where M is magnetization and H is magnetic field) of MgB_2 as a function of temperature, under conditions of zero field cooling (ZFC) and field cooling (FC) at 10 Oe. The existence of the superconducting phase was then confirmed

unambiguously by measuring the Meissner effect on cooling in a magnetic field. The onset of a well-defined Meissner effect was observed at 39 K. A superconducting volume fraction of 49% under a magnetic field of 10 Oe was obtained at 5 K, indicating that the superconductivity is bulk in nature. The standard four-probe technique was used for resistivity measurements. 中文

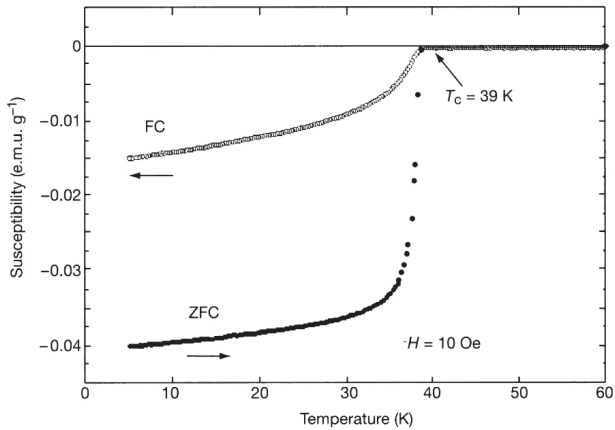
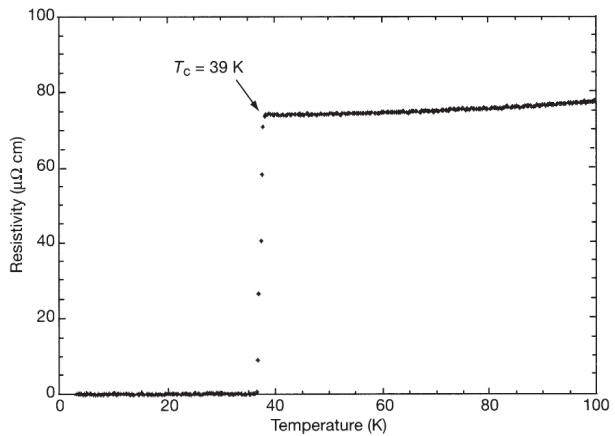


Fig. 3. Magnetic susceptibility χ of MgB₂ as a function of temperature. Data are shown for measurements under conditions of zero field cooling (ZFC) and field cooling (FC) at 10 Oe.

中文

Figure 4 shows the temperature dependence of the resistivity of MgB₂ under zero magnetic field. The onset and end-point transition temperatures are 39 K and 38 K, respectively, indicating that the superconductivity was truly realized in this system. 中文



(410, 63-64; 2001)

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Received 24 January; accepted 5 February 2001.

References:

1. Takagi, H. in *Proc. Int. Conf. on Materials and Mechanisms of Superconductivity, High Temperature Superconductors VI. Physica C* **341-348**, 3-7 (2000).
2. Tanigaki, K. *et al.* Superconductivity at 33 K in $\text{Cs}_x\text{Rb}_y\text{C}_{60}$. *Nature* **352**, 222-223 (1991).
3. Cava, R. V. *et al.* Superconductivity near 30 K without copper: the $\text{Ba}_{0.6}\text{K}_{0.4}\text{BiO}_3$ perovskite. *Nature* **332**, 814-816 (1988).
4. Schön, J. H., Kloc, Ch. & Batlogg, B. Superconductivity at 52 K in hole-doped C_{60} . *Nature* **408**, 549-552 (2000).
5. Jones, M. & Marsh, R. The preparation and structure of magnesium boride, MgB_2 . *J. Am. Chem. Soc.* **76**, 1434-1436 (1954).

Acknowledgements. This work was partially supported by a Grant-in-Aid for Science Research from the Ministry of Education, Science, Sports and Culture, Japan and by a grant from CREST.

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二硼化镁在39 K时的超导性

永松纯等

到2001年为止，在温度超过130 K的多种基于铜氧化物的材料中已观测到超导性。本文中物理学家永松纯及其同事们报道了在温度“仅仅为”39 K时观测到的超导性，但这是在一种非常不一样的材料中观测到的：金属化合物二硼化镁。这项工作创造了金属化合物超导转变温度的一个新纪录，因为从1973年到此之前，这种转变温度最高只有23 K。后续的工作表明，尽管存在一些特殊性，这种化合物的性质符合标准的BCS（巴丁-库珀-施里弗）超导理论。由于原料和制造成本低，二硼化镁已被广泛地用于超导体的实际应用中。

英文

鉴于在提高铜氧化物的超导转变温度上所取得的巨大成就（见参考文献1中的综述），其他类型材料的超导转变温度 T_c 可以被提高到何种程度自然而然地引起了人们的关注。现有报道中，非铜氧化物体超导性的 T_c 最高值，在电子掺杂的 $Cs_xRb_yC_{60}$ 中为33 K（参考文献2），在 $Ba_{1-x}K_xBiO_3$ 中为30 K（参考文献3）。（近期发现空穴掺杂的 C_{60} 超导转变温度 T_c 高达52 K^[4]，尽管那次实验的原本目的是为了揭示超导电流仅局限于 C_{60} 晶体表面，而非检测整体。）本文中报告了二硼化镁（ MgB_2 ）中体超导的发现。磁化和电阻测量表明超导转变温度为39 K，我们相信这是非铜氧化物体超导的至今为止所确定的最高转变温度。

英文

样品是用粉末状镁（Mg；99.9%）和粉末状的非晶硼（B；99%）在干燥箱中制备的。两种粉末以适当的比例（Mg:B=1:2）混合，研磨并挤压成圆片。将这些圆片置于热等静压（HIP）炉（O₂Dr.HIP，日本神

钢集团) 中, 在196 Mpa的高氩压强和973 K的温度下加热10小时。粉末X射线衍射通过带有石墨单色仪的常规X射线光谱仪 (RINT-2000, 日本理学公司) 来进行。强度数据利用Cu靶的 $K\alpha$ 辐射采集, 2θ 范围从 5° 到 80° , 步长宽度为 0.02° 。 [英文](#)

图1为一种典型的在室温下获取的 MgB_2 的X射线衍射图。假定一种六方晶胞, 其 $a=3.086 \text{ \AA}$, $c=3.524 \text{ \AA}$, 可以将所有高强度的峰进行标记。图2展示了 MgB_2 的晶体结构 (参考文献5), 空间群为 $P6_3/mmm$ (编号191)。如图2所示, 硼原子是按层排列的, 镁层交错插入硼层。每一层的硼原子结构与石墨每层的结构相同: 其中每个硼原子与其他三个硼原子是等距的。因此, MgB_2 是由两层硼以及一层镁沿六方晶格 c 轴构成的。 [英文](#)

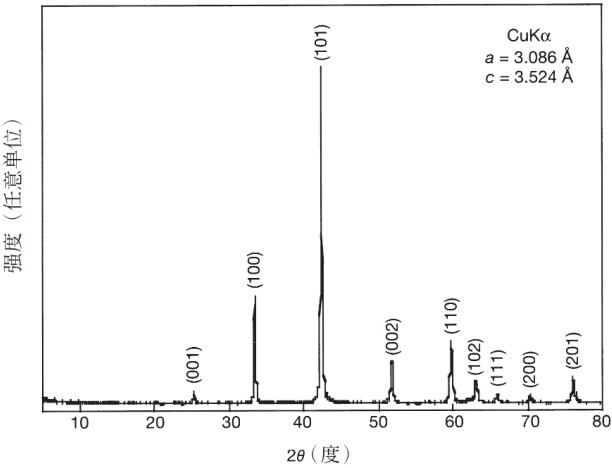


图1．室温下 MgB_2 的典型X射线衍射图 [英文](#)

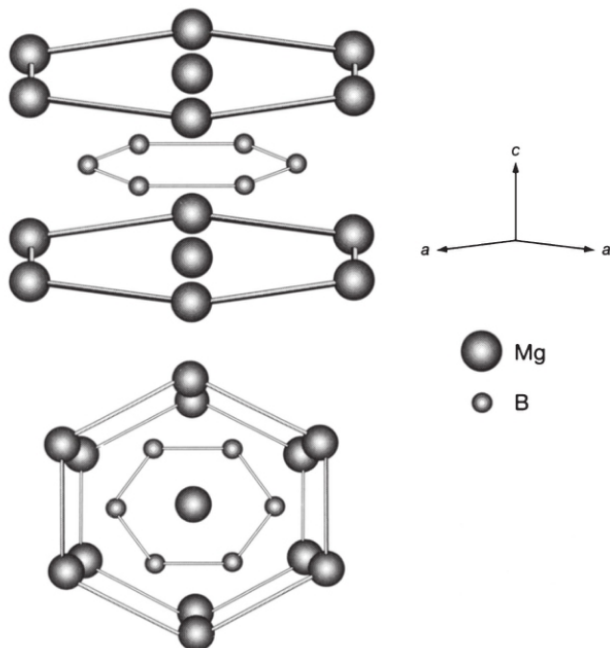


图2 . MgB₂的晶体结构 [英文](#)

磁化强度测量同样是通过超导量子干涉磁强计（SQUID）完成（MPMSR2，Quantum Design）。图3显示了MgB₂的磁化率（ $\chi = M / H$ ，其中 M 为磁化强度， H 为磁场）在零场冷却（ZFC）以及在10 Oe的场冷却（FC）条件下随温度变化的曲线。通过测量在磁场中冷却状态下的迈斯纳效应，明确地证实了超导相的存在。在温度为39 K时，开始观测到明确的迈斯纳效应。在温度为5 K时，10 Oe磁场下超导体积分数为49%，这就表明本质上是体超导性。在电阻测量中我们使用的是常规的四探针技术。 [英文](#)

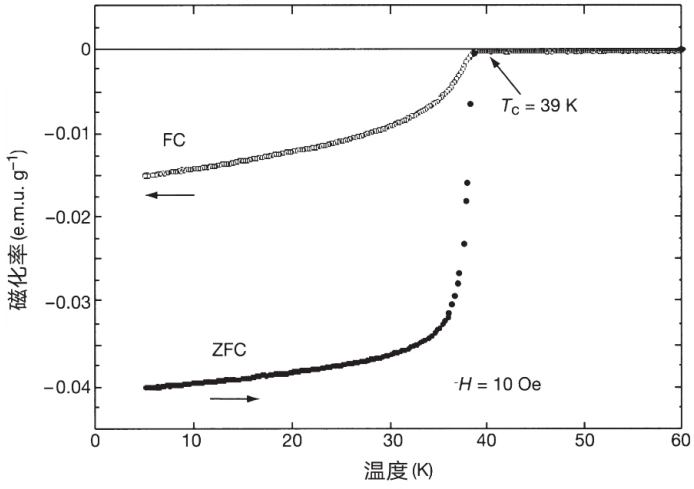


图3．MgB₂的磁化率 χ 随温度的变化。数据分别表示在零场冷却（ZFC）以及在10 Oe的场冷却（FC）条件下的测量结果。[英文](#)

图4显示了MgB₂在零磁场下电阻率随温度的变化关系。转变温度的起止点分别出现在39 K和38 K，这就表明在该系统中真正实现了超导性。[英文](#)

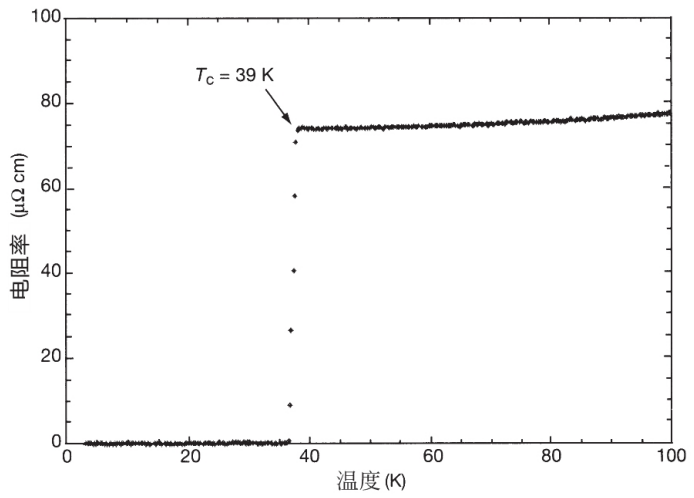


图4．零磁场下MgB₂的电阻率随温度的变化关系[英文](#)

（崔宁 翻译；韩汝珊 郭建栋 审稿）

Observation of High-energy Neutrinos Using Čerenkov Detectors Embedded Deep in Antarctic Ice

E. Andrés *et al.*

Neutrinos are chargeless and almost massless elementary particles. They interact with other matter only through the weak force, and therefore can penetrate large amounts of matter—neutrinos from the Sun are constantly streaming through the Earth. This weak interaction makes them difficult to detect. Here an international team of scientists report a proof-of-concept experiment called AMANDA, in which they set detectors in clear ice in the Antarctic and looked for the characteristic flashes of light emitted when a particle called a muon is created by interaction of a neutrino with an atomic nucleus. A subsequent project using a much larger volume of ice as the detector, called IceCube, is now operating near the South Pole. [中文](#)

Neutrinos are elementary particles that carry no electric charge and have little mass. As they interact only weakly with other particles, they can penetrate enormous amounts of matter, and therefore have the potential to directly convey astrophysical information from the edge of the Universe and from deep inside the most cataclysmic high-energy regions¹. The neutrino's great penetrating power,

however, also makes this particle difficult to detect. Underground detectors have observed low-energy neutrinos from the Sun and a nearby supernova², as well as neutrinos generated in the Earth's atmosphere. But the very low fluxes of high-energy neutrinos from cosmic sources can be observed only by much larger, expandable detectors in, for example, deep water^{3,4} or ice⁵. Here we report the detection of upwardly propagating atmospheric neutrinos by the ice-based Antarctic muon and neutrino detector array (AMANDA). These results establish a technology with which to build a kilometre-scale neutrino observatory necessary for astrophysical observations¹. [中文](#)

HIGH-ENERGY neutrinos must be generated in the same astrophysical sources that produce high-energy cosmic rays¹. These sources are a matter of speculation, but are thought to reside in shocked or violent environments such as are found in supernova remnants, active galactic nuclei, and gamma-ray bursters. The interaction of any high-energy proton or nucleus with matter or radiation in the source will produce neutrinos, some of which will have line-of-sight trajectories to Earth. AMANDA detects neutrinos with energies above a few tens of GeV by observing the Čerenkov radiation from muons that are produced in neutrino–nucleon interactions in the ice surrounding the detector or in the bedrock below⁶. This Čerenkov light is detected by an array of photomultiplier tubes (Fig. 1), which are buried deep in the ice in order to minimize the downward flux of muons produced in cosmic-ray interactions in the atmosphere. These muons constitute the main background for AMANDA. To ensure that the detected muons are produced by a neutrino, we use the Earth as a filter and look for upwardly propagating muons that perforce must have been produced by a neutrino that passed through the Earth. From the relative arrival times of the Čerenkov photons, measured with a precision of a few

nanoseconds, we can reconstruct the track of the muon. The direction of the neutrino and muon are collinear within an angle $\theta_{\nu-\mu} \approx 1.5/\sqrt{E_\nu}$ degrees, where E_ν is measured in TeV, thus enabling us to search for point sources of high energy neutrinos. 中文

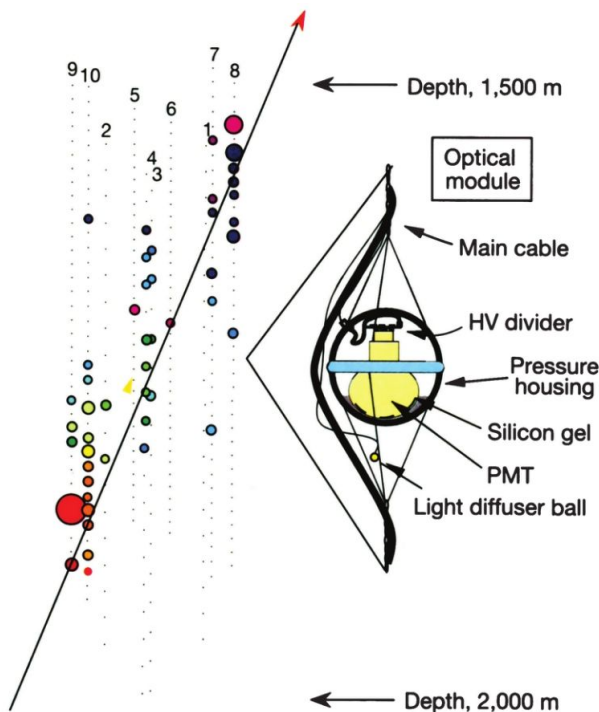


Fig. 1. The AMANDA-B10 detector and a schematic diagram of an optical module. Each dot represents an optical module. The modules are separated by 20 m on the inner strings (1 to 4), and by 10 m on the outer strings (5 to 10). The coloured circles show pulses from the photomultipliers for a particular event; the sizes of the circles indicate the amplitudes of the pulses and the colours correspond to the time of a photon's arrival. Earlier times are in red and later ones in blue. The arrow indicates the reconstructed track of the upwardly propagating muon. 中文

Upwardly propagating atmospheric neutrinos are a well understood source that can be used to verify the detection technique. The results reported here are from analyses of experimental data acquired in 138 days of net operating time during the Antarctic winter of 1997. At that time the detector consisted of 302 optical modules deployed on ten strings at depths of between 1,500 m and 2,000 m (Fig. 1). The instrumented volume is a cylinder of approximately 120 m in

diameter and 500 m in height. An optical module consists of an 8-inch photomultiplier tube housed in a glass pressure vessel. A cable provides the high voltage and transmits the anode current signals to the data acquisition electronics at the surface. Figure 1 also shows a representative event that has satisfied the selection criteria for an upwardly moving muon. The effective detection area for muons varies from about 3,000 m² at 100 GeV to about 4×10^4 m² for the higher-energy muons (≥ 100 TeV) that would be produced by neutrinos coming from, for example, the same cosmic sources that produce gamma-ray bursts⁷. [中文](#)

Because a knowledge of the optical properties of the ice is essential for track reconstruction, these have been studied extensively^{8,9}. The absorption length of blue and ultraviolet light (the relevant wavelengths for our purposes) varies between 85 m and 225 m, depending on depth. The effective scattering length, which combines the mean free path λ with the average scattering angle θ through $\lambda/(1 - \langle \cos\theta \rangle)$, varies from 15 m to 40 m. In order to reconstruct the muon tracks we use a maximum-likelihood method, which incorporates the scattering and absorption of photons as determined from calibration measurements. A bayesian formulation of the likelihood takes into account the much larger rate of downward muons relative to the upward signal and is particularly effective in decreasing the chance for a downward muon to be mis-reconstructed as upward. (See refs 6 and 10–13 for more information on optical properties of ice, calibration, and analysis techniques.) [中文](#)

Certain types of events that might appear to be upwardly propagating muons must be considered and eliminated. Rare cases, such as muons that undergo catastrophic energy loss through bremsstrahlung, or that are coincident with other muons, must be investigated. To this end, a series of requirements or quality criteria, based on the characteristic time and spatial pattern of photons associated with a muon track and

the response of our detector, are applied to all events that, in a first assessment, appear to be upwardly moving muons. For example, an event that has a large number of optical modules hit by prompt (that is, unscattered) photons, has a high quality. By making these requirements (or “cuts”) increasingly selective, we eliminate correspondingly more of the background of false upward events while still retaining a significant fraction of the true upwardly moving muons. Because there is a large space within which the parameters defining these cuts can be optimized, two different and independent analyses of the same set of data have been undertaken. These analyses yielded comparable numbers of upwardly propagating muons (153 in analysis A, 188 in analysis B). Comparison of these results with their respective Monte Carlo simulations shows that they are consistent with each other in terms of the number of events, the number of events in common and, as discussed below, the expected properties of atmospheric neutrinos. [中文](#)

In Fig. 2a, the number of experimental events is compared to simulations of background and signal as a function of the (identical) quality requirements placed on the three types of events: experimental data, simulated upwardly moving muons from atmospheric neutrinos, and a simulated background of downwardly moving cosmic-ray muons. For simplicity in presentation, the levels of the individual cuts have been combined into a single parameter representing the overall event quality. Figure 2b shows ratios of the quantities plotted above. As the quality level is increased, the ratios of simulated background to experimental data, and of experimental data to simulated signal, both continue their rapid decrease, the former toward zero and the latter toward 0.7. Over the same range, the ratio of experimental data to the simulated sum of background and signal remains nearly constant. We conclude that the quality requirements have reduced the presence of wrongly reconstructed downward muons in the experimental data to a negligible fraction of the signal and that the experimental data behave

in the same way as the simulated atmospheric neutrino signal for events that pass the stringent cuts. The estimated uncertainty on the number of events predicted by the signal Monte Carlo simulation, which includes uncertainties in the high-energy atmospheric neutrino flux, the *in situ* sensitivity of the optical modules, and the precise optical properties of the ice, is +40% / -50%. The observed ratio of experiment to simulation (0.7) and the expectation (1.0) therefore agree within the estimated uncertainties. 中文

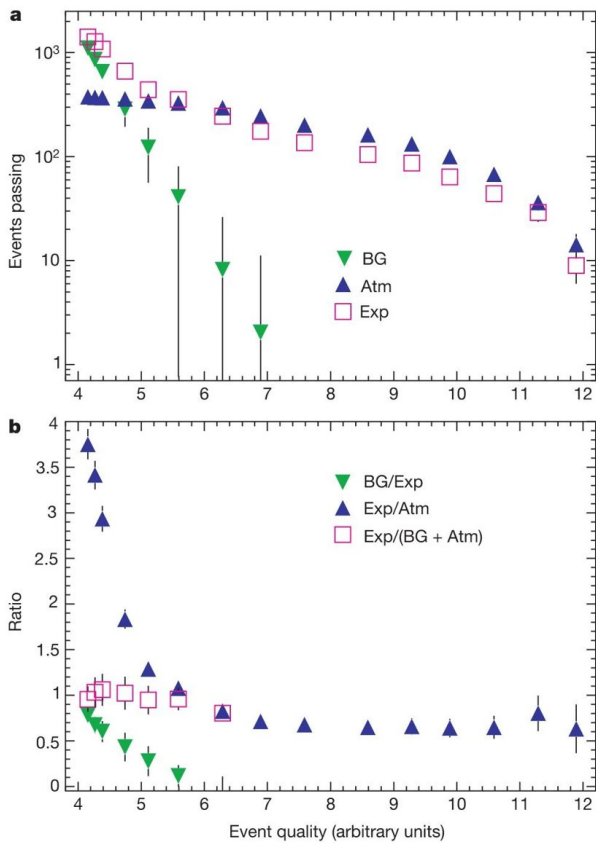


Fig. 2. Experimental data confront expectations. The numbers of reconstructed upwardly moving muon events for the experimental data (Exp) from analysis A are compared to simulations of background cosmic-ray muons (BG) and simulations of atmospheric neutrinos (Atm) as a function of “event quality”, a variable indicating the combined severity of the cuts designed to enhance the signal. The comparison begins at a quality level of 4. Cuts were made on a number of parameters including the reconstructed zenith angle (>100 degrees), maximum likelihood of the reconstruction, topological distributions of the detected photons, and the number of optical modules recording unscattered photons. The optimum levels of the

cuts were determined by comparing the relative rejection rates for Monte Carlo simulated neutrino events and background events. **b**, Ratios of the quantities shown in **a**. [中文](#)

The shape of the zenith-angle distribution of the 188 events from analysis B is compared to a simulation of the atmospheric neutrino signal in Fig. 3, where the absolute Monte Carlo rate has been normalized to the experimental rate. The variation of the measured rate with zenith angle is reproduced by the simulation to within the statistical uncertainty. We note that the tall geometry of the detector favours the more vertical muons. The arrival directions of the upwardly moving muons observed in both analyses are shown in Fig. 4. A statistical analysis indicates no evidence for point sources in these samples. The agreement between experiment and simulation of atmospheric neutrino signal, as demonstrated in Figs 2 and 3, taken together with comparisons for a number of other variables (to be published elsewhere) leads us to conclude that the upcoming muon events observed by AMANDA are produced mainly by atmospheric neutrinos with energies of about 50 GeV to a few TeV. The background in this event sample is estimated to be $15 \pm 7\%$ events, and is due to misreconstructions. [中文](#)

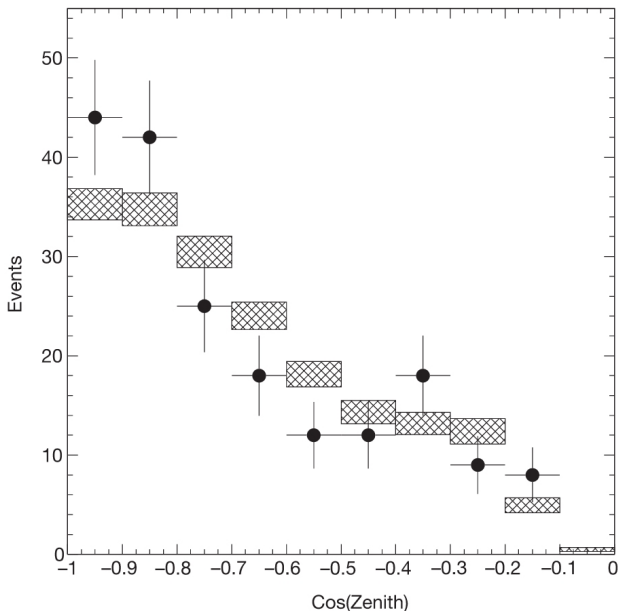


Fig. 3. Reconstructed zenith angle distribution. The data points are experimental data (from analysis B) and the shaded boxes are a simulation of atmospheric neutrino events, the widths of the boxes indicating the error bars. The overall normalization of the simulation has been adjusted to fit the data. The possible effects of neutrino oscillations on the flux and its zenith angle dependence estimated from the Super-Kamiokande measurements²⁰, are expected to be small in our energy range. 中文

From the consistency of the selected event sample with muons generated by atmospheric neutrinos, and in particular the absence of an excess of high-energy events with a large number of optical modules that had been hit, we can determine an upper limit on a diffuse extraterrestrial neutrino flux. Assuming a hard E^{-2} spectrum characteristic of shockwave acceleration, we expect to reach a sensitivity of order $dN/dE_\nu = 10^{-6} E_\nu^{-2} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$. This value is low enough to be in the range where a number of models¹⁴⁻¹⁹ predict fluxes, a few of which are larger^{15,16}. Most recent estimates are smaller¹⁷⁻¹⁹. The present level of sensitivity and the prospects for improving it through longer exposure times and better determination of muon energy illustrate the ability of large-area detectors to test theoretical models that assume the hadronic origin of TeV photons from active galaxies—models which would be difficult to confirm or exclude without the ability to observe high-energy neutrinos. 中文

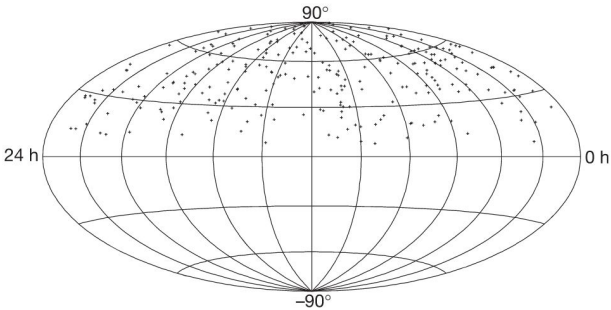


Fig. 4. Distribution in declination and right ascension of the upwardly propagating events on the sky. The 263 events shown here are taken from the upward muons contained in both analysis A and analysis B. The median difference between the true and the reconstructed muon angles is about 3 to 4 degrees. 中文

Searches for neutrinos from gamma-ray bursts, for magnetic monopoles, supernova collapses and for a cold dark matter signal from

the centre of the Earth are also in progress and, with only 138 days of data, yield limits comparable to or better than those from smaller underground neutrino detectors that have operated for a much longer period (see refs 10–13). 中文

From 1997 to 1999 an additional nine strings were added in a concentric cylinder around AMANDA-B10. This larger detector, called AMANDA-II, consists of 677 optical modules and has an improved acceptance for muons over a larger angular interval. Data are being taken now with the larger array. Yet the fluxes of very high energy neutrinos predicted by theoretical models¹⁴ or derived from the observed flux of ultra high energy cosmic rays¹⁹ are sufficiently low that a neutrino detector having an effective area up to a square kilometre is required for their observation and study^{1,14}. Plans are therefore being made for a much larger detector, IceCube, consisting of 4,800 photomultipliers to be deployed on 80 strings. This proposed neutrino telescope would have an effective area of about 1 km², an energy threshold near 100 GeV and a pointing accuracy for muons of better than one degree for high-energy events. In conclusion, the observation of neutrinos by a neutrino telescope deep in the Antarctic ice cap, a goal that was once thought difficult if not impossible, represents an important step toward establishing the field of high-energy neutrino astronomy first envisioned over 40 years ago. 中

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(410, 441-443; 2001)

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Received 15 September 2000; accepted 25 January 2001.

References:

1. Gaisser, T. K., Halzen, F. & Stanev, T. Particle physics with high-energy neutrinos. *Phys. Rep.* **258**, 173-236 (1995).
2. Totsuka, Y. Neutrino astronomy. *Rep. Prog. Phys.* **55**, 377-430 (1992).
3. Roberts, A. The birth of high-energy neutrino astronomy: A personal history of the DUMAND project. *Rev. Mod. Phys.* **64**, 259-312 (1992).
4. Balkanov, V. A. *et al.* An upper limit on the diffuse flux of high energy neutrinos obtained with the Baikal detector NT-96. *Astropart. Phys.* **14**, 61-67 (2000).
5. Lowder, D. M. *et al.* Observation of muons using the polar ice as a Čerenkov detector. *Nature* **353**, 331-333 (1991).
6. Andres, E. *et al.* The AMANDA neutrino telescope: Principle of operation and first results. *Astropart. Phys.* **13**, 1-20 (2000).

7. Waxman, E. & Bahcall, J. N. High-energy neutrinos from cosmological gamma ray burst fireballs. *Phys. Rev. Lett.* **78**, 2292-2295 (1997).
8. Askjeber, P. *et al.* Optical properties of the south pole ice at depths between 0.8 and 1 km. *Science* **267**, 1147-1150 (1995).
9. Price, B. P. Implications of optical properties of ocean, lake, and ice for ultrahigh-energy neutrino detection. *Appl. Opt.* **36**, 1965-1975 (1997).
10. Wischniewski, R. *et al.* in *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City* Vol. 2 (eds Kieda, D., Salamon, M. & Dingus, B.) 229-232 (1999).
11. Dalberg, E. *et al.* in *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City* Vol. 2 (eds Kieda, D., Salamon, M. & Dingus, B.) 348-351 (1999).
12. Bay, R. *et al.* in *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City* Vol. 2 (eds Kieda, D., Salamon, M. & Dingus, B.) 225-228 (1999).
13. Niessen, P. *et al.* in *Proc. 26th Int. Cosmic Ray Conf., Salt Lake City* Vol. 2 (eds Kieda, D., Salamon, M. & Dingus, B.) 344-347 (1999).
14. Learned, J. G. & Mannheim, K. High-energy neutrino astrophysics. *Ann. Rev. Nucl. Sci.* **50**, 679-749 (2000).
15. Szabo, A. P. & Protheroe, R. J. Implications of particle acceleration in active galactic nuclei for cosmic rays and high-energy neutrino astronomy. *Astropart. Phys.* **2**, 375-392 (1994).
16. Stecker, F. W. & Salamon, M. H. High-energy neutrinos from quasars. *Space Sci. Rev.* **75**, 341-355 (1996).
17. Nellen, L., Mannheim, K. & Biermann, P. L. Neutrino production through hadronic cascades in AGN accretion disks. *Phys. Rev. D* **47**, 5270-5274 (1993).
18. Mannheim, K., Protheroe, R. J. & Rachen, J. P. Cosmic ray bound for models of extragalactic neutrino production. *Phys. Rev. D* **63**, 023003-1-023003-16 (2001).
19. Waxman, E. & Bahcall, J. N. High energy neutrinos from astrophysical sources. An upper bound. *Phys. Rev. D* **59**, 023002-1-023002-8 (1999).
20. Fukuda, Y. *et al.* (Super-Kamiokande Collaboration) Measurement of the flux and zenith-angle distribution of upward through-going muons by Super-Kamiokande. *Phys. Rev. Lett.* **82**, 2644-2648 (1999).

Acknowledgements. This research was supported by the following agencies: US National Science Foundation, Office of Polar Programs; US National Science Foundation, Physics Division; University of Wisconsin Alumni Research Foundation; US Department of Energy; Swedish Natural Science Research Council; Swedish Polar Research Secretariat; Knut and Alice Wallenberg Foundation, Sweden; German Ministry for Education and Research; US National Energy Research Scientific Computing Center (supported by the Office of Energy Research of the US Department of Energy); UC-Irvine AENEAS Supercomputer Facility; Deutsche Forschungsgemeinschaft (DFG). D.F.C. acknowledges the support of the NSF CAREER programme and C.P.d.l.H. acknowledges support from the European Union 4th Framework of Training and Mobility of Researchers.

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借助南极冰下深处的切伦科夫探测器观测高能中微子

安德烈斯等

中微子是无电荷且几乎无质量的基本粒子。它们只能通过弱力与其他物质相互作用，因此可以穿透大量物质——来自太阳的中微子就不断地流经地球。这种弱相互作用使中微子难以被检测。本文中，一个国际科学家团队报告了名为AMANDA的概念验证型实验，他们将探测器设置在南极透明的冰层中，并寻找由中微子与原子核相互作用而产生的被称为 μ 子的粒子发出的特征性闪光。随后的冰立方（IceCube）项目使用更大体量的冰作为探测器，目前已在南极附近运行。 [英文](#)

中微子是一种不携带电荷且质量极小的基本粒子。由于这类粒子与其他粒子的相互作用很弱，能够穿透大量的物质，因此很可能可以直接传递来自宇宙边缘以及大部分高能激变区域深处的天体物理信息^[1]。然而，中微子极强的穿透力也使得对该粒子的探测变得非常困难。在以前的研究中，研究人员通过地下探测器已经探测到来自太阳和附近超新星的低能中微子^[2]，以及地球大气中产生的中微子。但是，来自宇宙源的高能中微子通量很低，只能通过更大的、可扩展的探测器才能观测到，比如放置于深水^[3,4]或冰^[5]中的探测器。本文将报道通过基于冰的南极 μ 子和中微子探测器阵列（AMANDA）对向上传播的大气中微子的探测。这些结果将确立一种技术，可以用于建设千米尺度的中微子天文台，从而用于天体物理的观测^[1]。 [英文](#)

发射高能宇宙射线的天体物理源也必然产生高能中微子^[1]。这些源

目前尚属推测，但是一般认为存在于极端剧烈环境中，比如超新星遗迹、活动星系核和伽马射线暴。这些源中，任何高能质子或原子核与物质或辐射相互作用，都会产生中微子，其中一些将具有指向地球的视线径迹。中微子与探测器周围冰层或底下岩床中的核子相互作用可以产生 μ 子。通过探测 μ 子发出的切伦科夫辐射，AMANDA可以探测到能量高于数十GeV的中微子[6]。图1给出了我们用于探测切伦科夫辐射的光电倍增管阵列，它们被埋设于冰层深处，以最大限度地减小大气中宇宙射线相互作用产生的 μ 子的向下通量。这些大气 μ 子构成了AMANDA的主要背景信号。为了确保探测到的 μ 子确实产生于中微子，我们将整个地球作为一个大过滤器，探测那些一定是由穿过地球的中微子产生的向上传播的 μ 子。探测器探测到的切伦科夫光子的相对到达时间的精度在纳秒量级，我们通过记录这些到达时间可以重建 μ 子的径迹。中微子与 μ 子的方向在夹角 $\theta_{\nu-\mu} \approx 1.5^\circ / (E_\nu)^{1/2}$ 内共线，其中 E_ν 单位为TeV，这可以使我们寻找高能中微子点源。

英文

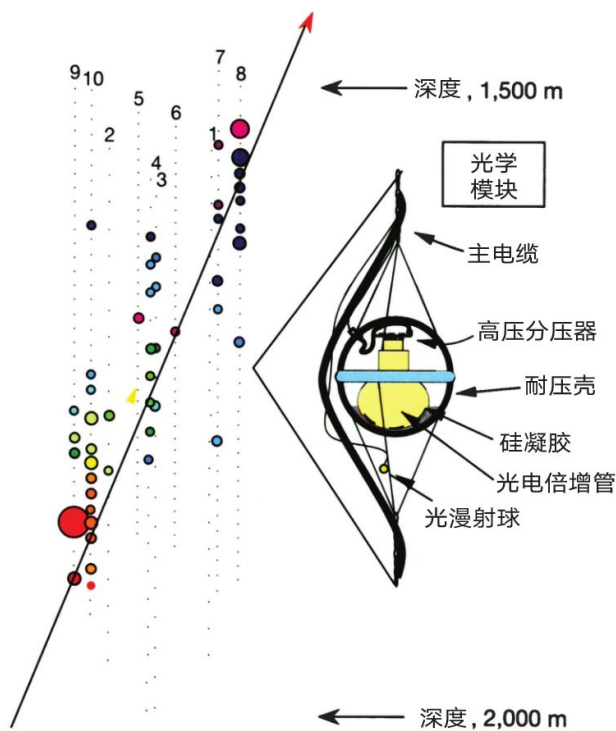


图1 . AMANDA-B10探测器及其光学模块原理图。图中每个小点代表一个光学模块。在内部串，光学模块之间的距离为20 m (1到4)；在外部串，模块之间的距离为10 m (5到10)。不同颜色的圆圈表示某个事例中光电倍增管产生的脉冲，其中圆圈的尺寸大小代表该脉冲的幅度，颜

色对应光子到达的时间。较早的时间用红色表示，较晚的时间用蓝色表示。图中箭头表示斜向上运动的 μ 子的重建径迹。 [英文](#)

向上传播的大气中微子作为源已经为人们所了解，因此可以用大气中微子验证我们的探测技术。我们分析了在1997年南极冬季获取的138天净运转时间的实验数据，并将结果在本文中予以报告。当时，实验采用的探测器由302个光学模块构成，这些模块埋设为10串，深度在1,500 m到2,000 m之间（图1）。整个探测器设备是一个圆柱体，其直径大约为120 m，高度约为500 m。每个光学模块包括一个封装于玻璃质压力容器中的8英寸光电倍增管。一根电缆用于提供光电倍增管所需的高电压，并将阳极电流信号传输到位于地面的数据采集电子设备。图1中也给出了一个满足向上运动的 μ 子选择标准的典型事件。根据 μ 子能量的不同，探测系统的有效探测面积范围从3,000 m²到40,000 m²，对应从100 GeV到高能 μ 子（ ≥ 100 TeV）的情形，产生后者的中微子应该来自宇宙源，比如同样产生伽马射线暴的宇宙源^[7]。 [英文](#)

为了重建中微子的径迹，首先要弄清冰的光学特性。人们对此已进行了广泛的研究^[8,9]。根据冰层深度的不同，蓝光和紫外光（我们所用的相关波长）的吸收长度在85 m到225 m之间变化。由平均自由程 λ 和平均散射角 θ 构成的有效散射长度 $\lambda/(1 - \langle \cos\theta \rangle)$ 为15~40 m。我们采用最大似然方法重建 μ 子径迹，考虑了通过刻度测量得到的光子的散射和吸收。考虑到向下 μ 子的事例率远远大于向上的信号，对似然值的贝叶斯分析可以有效减小将向下 μ 子错误重建为向上 μ 子的可能性。（参考文献6以及10~13介绍了更多关于冰的光学特性、刻度以及分析技术。） [英文](#)

在探测过程中，可能存在某些看似是向上传播的 μ 子的伪事件，对这种情况必须予以考虑并剔除。同时，也必须要考虑那些罕见的情况，比如 μ 子经过韧致辐射损失了大部分能量，或者与其他 μ 子同时出现的情况。为此，一系列基于 μ 子径迹预期产生的光子时间和空间特征图样以及基于探测器的响应的要求或者说质量标准在首次评估中用于筛选那些看似是向上运动的 μ 子事件。比如，瞬发（即未被散射）光子触发大量光学模块，该事件就具有较高的品质。通过不断提高选择的标准（或者说“判选”），我们可以相应地剔除更多的向上 μ 子伪事件背景，同时仍然

保留大部分真正向上运动的 μ 子。由于构成筛选标准的各参数具有较大的优化空间，我们对相同的实验数据进行了两种不同且互相独立的分析，分别称为A分析和B分析。A、B两种分析结果给出的向上运动的 μ 子数目相当，分别为153和188。这两个结果分别与其相应的蒙特卡罗模拟进行比较，发现二者在事件数目、共同事件数目以及如下所述的大气中微子预期特性方面彼此一致。 [英文](#)

如图2a所示，我们将实验事件的数量与背景和信号的模拟结果作为（相同）品质判据的函数进行了对比，对以下三类事件——实验数据、模拟的大气中微子产生的向上运动的 μ 子、模拟的向下运动的宇宙射线 μ 子背景——进行了分析。为了简化演示，多个筛选标准合并成了一个代表整体事件品质的参数。图2b显示了图2a绘制的数量间的比值。随着品质水平的增加，模拟背景与实验数据的比值以及实验数据与模拟信号的比值，同时迅速减小，其中前者趋于0而后者趋于0.7。在上述范围内，实验数据与另两者（模拟的背景和信号）之和的比值几乎保持不变。因此，我们得出以下结论：品质筛选标准可以剔除实验数据中误重建的向下运动的 μ 子，直至与信号相比达到可以忽略的水平；经过严格筛选后，实验数据与模拟大气中微子信号的行为规律相同。蒙特卡罗模拟预测的信号事件数的估算不确定度为+40% / -50%，该不确定度包括了高能大气中微子通量、光学模块的实地灵敏度以及冰层准确光学特性的不确定度。因此，在上述估算不确定度内，观察到的实验和模拟比值（0.7）与期望值（1.0）相符合。 [英文](#)

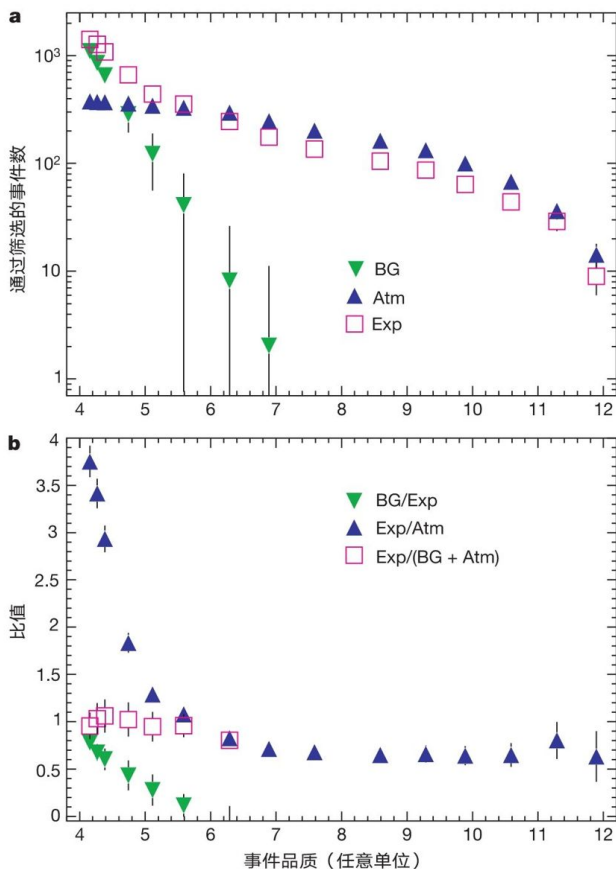


图2．实验数据与期望值比较。A分析中重建实验数据中向上运动的 μ 子事件的数目（用Exp表示），与模拟宇宙射线 μ 子背景（BG）以及模拟大气中微子（Atm），作为“事件品质”的函数进行了比较。其中“事件品质”这一变量表示用于增强信号的若干筛选标准的组合的严格程度。图中对比起始于品质水平4。筛选标准由若干参量构成，这些参量包括重建天顶角（ $>100^\circ$ ）、重建径迹的最大似然值、探测光子的拓扑分布以及记录未散射光子的光学模块数目。通过比较蒙特卡罗模拟中微子事件和背景事件的相对排斥率，可以确定筛选标准的最佳水平。b图给出了a图中数量的比值。 [英文](#)

图3给出了B分析中188个事件的天顶角分布与模拟大气中微子信号的对比，其中蒙特卡罗绝对事例率根据实验值进行了归一化。在统计不确定度之内，测量事例率随天顶角的变化与模拟结果一致。我们注意到，探测器较高的几何尺寸会更利于探测到垂直方向的 μ 子。在A和B两种分析中，观测到的向上运动的 μ 子的到达方向如图4所示。统计分析表明，这些样本尚不足以提供点源存在的证据。图2与图3已经证明实验与大气中微子信号模拟的一致性；同时对比其他变量（具体研究结果即将发表）的话，我们得出以下结论：AMANDA观测到的上行 μ 子事件主要

是由那些能量介于50 GeV到若干TeV之间的大气中微子产生。事件样本中的背景事件估计为 $15\% \pm 7\%$ ，这是由于错误的径迹重建造成的。

英文

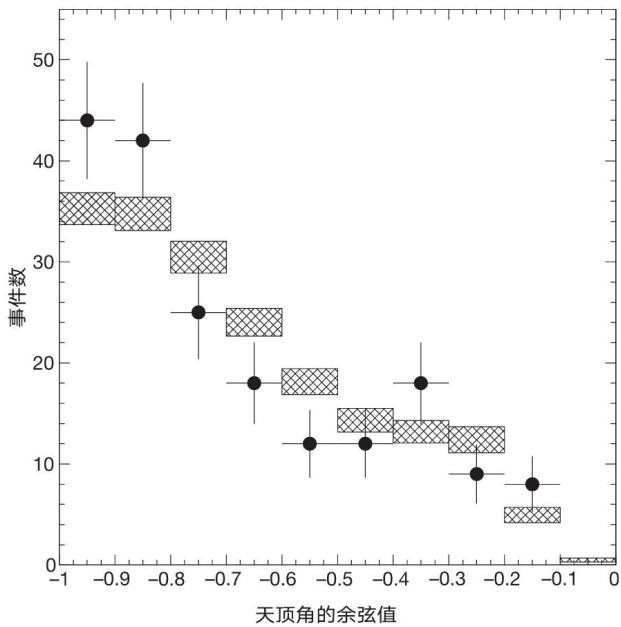


图3．重建径迹的天顶角分布。图中数据点是取自分析B的实验数据，阴影矩形框表示大气中微子事件的模拟，其中矩形框的宽度代表误差棒。模拟的整体归一化已经经过调整以拟合数据。中微子振荡对通量及通量的天顶角依赖的可能影响可以通过超级神冈实验的测量估算出来[20]，在我们研究的能量范围内，该影响预计很小。

英文

根据筛选的事件样本与大气中微子产生的 μ 子的一致性，特别是触发大量光学模块的高能事件不存在超出的情况下，我们可以确定地外弥散中微子通量的上限。假设激波加速具有 E^{-2} 形式的硬谱特征，那么我们预计灵敏度的量级将达到 $dN/dE_v = 10^{-6} E_v^{-2} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}^{-1}$ 。该值很小，位于很多模型预测的通量范围之内[14-19]，其中一些通量会更大些[15,16]。不过近期的估算值大多数相对更小[17-19]。我们设想可以通过更长时间的曝光以及更好地确定 μ 子的能量来改善灵敏度，目前的灵敏度水平和这些设想说明了大面积探测器检验理论模型的能力。这些理论模型假设活动星系发出的TeV能量的光子来源于强子，如果没有观测高能中微子能力，证实或排除这些模型将会非常困难。

英文

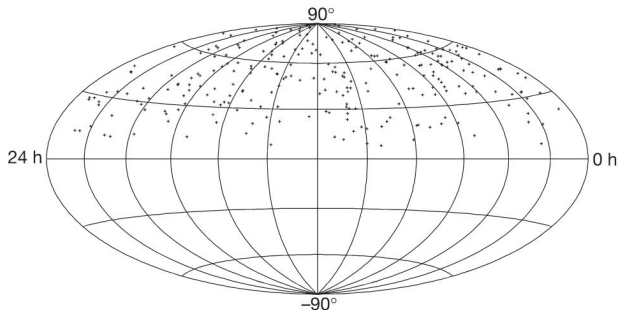


图4．向上传播的 μ 子事件在天空中赤纬和赤经上的分布。图中所示的263个事件取自A和B两个分析中包含的共同的上行 μ 子事件。 μ 子的真实角度和重建角度之差的中值约为3~4度。 [英文](#)

寻找来自伽马射线暴的中微子，寻找磁单极子和超新星坍缩，寻找来自地球中心的冷暗物质，这些工作也在进行之中。而且，仅使用138天的数据，就可给出与那些已长时间运行的小型地下中微子探测器相媲美或更好的上限（见参考文献10~13）。 [英文](#)

从1997年到1999年，在AMANDA-B10周围的同心圆柱体中又添加了9串探测器。这个更大的探测器被称为AMANDA-II，由677个光学模块构成，在更大的角度范围内改善了 μ 子的接收度。目前，这个更巨大的阵列正在采集数据。但是无论是理论模型预言^[14]还是由超高能宇宙射线通量观测值推导出的^[19]高能中微子通量都是非常低的，以至于为了观测研究这些中微子，探测器的有效面积需要达到一平方千米^[1,14]。所以，目前正在计划研制更大的探测器，该探测器被称为冰立方（IceCube），由分布在80根串上的4,800个光电倍增管构成。这一计划中的中微子探测器将具有1 km²大小的有效面积，其探测能量阈值接近100 GeV，对于高能事件的 μ 子的指向精度优于1度。总而言之，通过南极冰盖下的中微子望远镜观测到中微子意味着人们朝40多年前就试图建立的高能中微子天文学研究领域迈出了重要的一步，尽管这一设想一度被认为是极难甚至是无法实现的目标。 [英文](#)

（金世超 翻译；曹俊 审稿）

Upper Limits to Submillimetre-range Forces from Extra Space-time Dimensions

J. C. Long *et al.*

Gravity is the weakest of the four fundamental forces, being 40 orders of magnitude weaker than the electromagnetic force. In string theory—an attempt to unify the description of particles and forces—this weakness arises because the force is dissipated in six extra spatial dimensions that are “curled up” and therefore invisible to us. It has been suggested that the effect of these curled-up dimensions might become evident at very small length scales, whereby objects would feel more gravitation force at those scales. Here physicist Joshua Long and colleagues describe an experiment that looked for a deviation of the gravitational force from its familiar inverse-square law on length scales of 100 micrometres. They found no such deviation. [中文](#)

String theory is the most promising approach to the long-sought unified description of the four forces of nature and the elementary particles¹, but direct evidence supporting it is lacking. The theory requires six extra spatial dimensions beyond the three that we observe; it is usually supposed that these extra dimensions are curled up into small spaces. This “compactification” induces “moduli” fields, which describe the size and shape of the compact

dimensions at each point in space-time. These moduli fields generate forces with strengths comparable to gravity, which according to some recent predictions²⁻⁷ might be detected on length scales of about 100 μm . Here we report a search for gravitational-strength forces using planar oscillators separated by a gap of 108 μm . No new forces are observed, ruling out a substantial portion of the previously allowed parameter space⁴ for the strange and gluon moduli forces, and setting a new upper limit on the range of the string dilaton^{2,3} and radion⁵⁻⁷ forces. [中文](#)

THE combined potential energy V due to a modulus force and newtonian gravity may be written:

$$V = - \int d\mathbf{r}_1 \int d\mathbf{r}_2 \frac{G \rho_1(\mathbf{r}_1) \rho_2(\mathbf{r}_2)}{r_{12}} [1 + \alpha \exp(-r_{12}/\lambda)] \tag{1}$$

The first term is Newton’s universal gravitation law, with G the gravitational constant, r_{12} the distance between two points $\mathbf{r}_1$ and $\mathbf{r}_2$ in the test masses, and ρ_1 , ρ_2 the mass densities of the two bodies. The second term is a Yukawa potential, with α the strength of the new force relative to gravity, and λ the range. As for any force-mediating field, the range of the modulus force is related to its mass m by $\lambda = \hbar / mc$. Previous tests of Newtonian gravity and searches for new macroscopic forces have covered length scales from light-years to nanometres⁸⁻¹⁰, and it has been found that new forces of gravitational strength can be excluded for ranges λ from 200 μm to nearly a light-year^{8,11,12}, but limits on new forces become poor very rapidly below 200 μm (refs 9, 13). [中文](#)

The strange and gluon moduli arise in a scenario where supersymmetry (a hypothesized symmetry incorporated in string theory that relates bosons to fermions) is broken at 10–100 TeV, and all compactification occurs near the ultrahigh Planck scale of 10^{19}

GeV where gravity is unified (in these scenarios) with other forces. In this case a range of approximately a millimetre is specifically predicted. The dilaton is a scalar field required for the consistency of string theory whose vacuum value fixes the strength of the interaction between strings. It may be interpreted as the modulus describing the size of the tenth space dimension that is compactified in M-theory to yield string theory in nine space dimensions. (M-theory is the structure that unifies the various types of string theory into a single framework¹.) The strength α associated with the dilaton can be computed, but the range λ at present can only be constrained by experiment; little is known about the mechanism which gives the dilaton mass. The radion results from a very different scenario in which one or more dimensions compactify at TeV energy scales, but here a range λ accessible to our experiment is again predicted. 中文

The special significance of millimetre scales derives from a mass formula of the form $m \approx M^2 / M_P$, where M_P is the mass associated with the Planck scale, 10^{19} GeV / c^2 , and M is a mass of 1–100 TeV / c^2 , leading to λ in the centimetre to micrometre range. In the strange and gluon moduli case, M is the scale where supersymmetry breaking occurs, whereas in the radion modulus case it corresponds to the size of one or more compact dimensions. This formula also applies to the ADD theory¹⁴ (named for its authors) in which two compact extra dimensions of millimetre size modify gravity itself. In the ADD theory M is the fundamental length scale where all physics is unified while m is a mass corresponding to the size of the large compact extra dimensions. Many scenarios of compactification, symmetry breaking and mass generation are still viable, so although the possibility of observing new forces at millimetre scales is exciting, such experiments cannot currently falsify string theory. 中文

The planar geometry of our source and detector masses (Fig. 1) is

chosen to concentrate as much mass density as possible at the length scale of interest. It is approximately null with respect to the $1 / r^2$ newtonian background, a helpful feature in the context of a new force search. A cantilever mode (similar to the motion of a diving board) of the tungsten source mass is driven to a tip amplitude of $19\text{ }\mu\text{m}$ at the resonant frequency of the detector mass. The tungsten detector mass is a double torsional oscillator¹⁵; in the resonant mode of interest the two rectangular sections of the detector counter-rotate about the torsion axis, with most of the amplitude confined to the smaller rectangle under the source mass and shield. Torsional motion of the detector will be driven if a mass coupled force is present between the source and detector. The motions are detected with a capacitive transducer, followed by a preamplifier, filters and a lock-in amplifier. To suppress background forces due to electrostatics and residual gas, a stiff conducting shield is fixed between the test masses. With the source at rest, the gap between source and detector is adjusted to $108\text{ }\mu\text{m}$, and the entire apparatus is placed in a vacuum enclosure and maintained at pressures below 2×10^{-7} torr. 中文

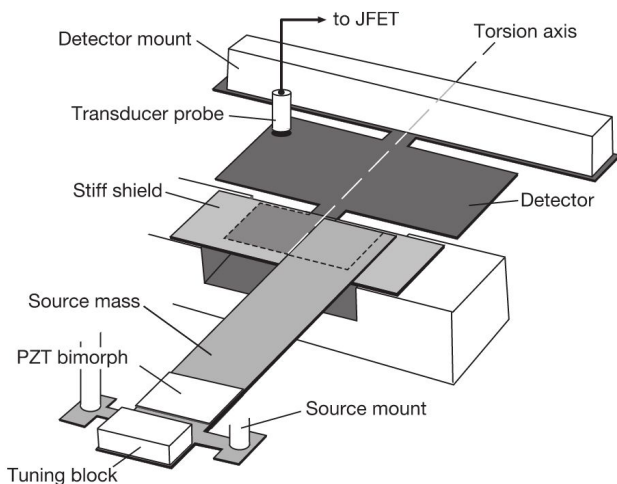


Fig. 1. Major components of the apparatus. The smaller rectangle of the tungsten detector (under the shield) is 11.455 mm wide, 5.080 mm long and $195\text{ }\mu\text{m}$ thick. The detector is annealed at $1,300\text{ }^{\circ}\text{C}$ to increase its mechanical Q to $25,000$. In operation the $1,173.085\text{-Hz}$ resonant frequency of the detector is stabilized by actively controlling the detector temperature to 305 K . The tungsten source mass is 35 mm long, 7 mm wide and $305\text{ }\mu\text{m}$

thick. The source mass resonant frequency is tuned to the detector and driven by the PZT (lead zirconate titanate) piezoelectric bimorph. The shield is a 60- μm -thick sapphire plate coated with 100 nm of gold on both sides. The test masses and the shield are supported by three separate five-stage passive vibration isolation stacks²³, each providing approximately 200-dB attenuation at 1 kHz. Mechanical probes are used to directly measure the relative orientation and position of each component, and to measure the source mass amplitude. Detector motions are sensed by a cylindrical capacitive probe supported 100 μm above a rear corner of the large rectangle of the detector mass. The probe is biased at 200 V through a 100 G Ω resistor, and connected to an SK 152 junction field-effect transistor (JFET) through a blocking capacitor. The JFET noise temperature of 100 mK is more than sufficient to detect 305 K thermal motions of the detector mass. The JFET preamplifier is followed by a second preamplifier, filters, and finally a two-phase lock-in amplifier. The total voltage gain from the capacitive probe to the lock-in input is approximately 1,600. A crystal-controlled oscillator provides a reference signal for the lock-in amplifier and drives the source mass PZT through a 1:10 step-up transformer. 中文

Figure 2 shows histograms of the raw data, collected with the source mass drive tuned both on and off the detector resonant frequency. Each plot contains data from one channel of the lock-in amplifier, corresponding to one of two orthogonal phases of the detector motion at the drive frequency. The widths of the off-resonance distributions are due to preamplifier noise, whereas the on-resonance distributions are due to the sum of preamplifier noise and detector thermal motions. The on- and off-resonance means shown in Fig. 3 agree within their standard deviations, indicating the absence of a significant resonant force signal. 中文

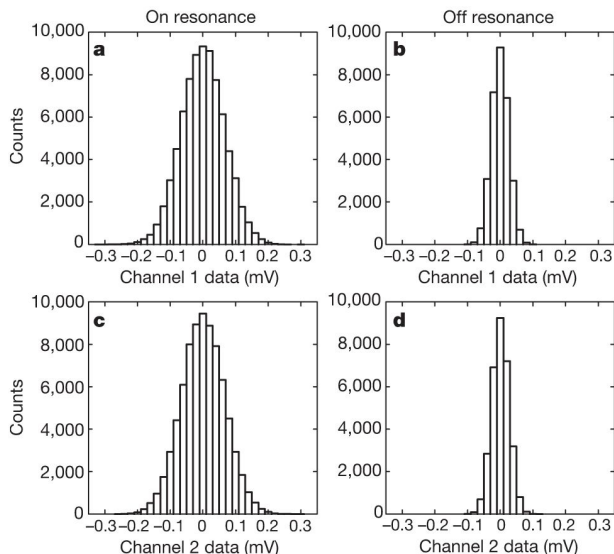


Fig. 2. Distributions of data samples. Data were recorded at 1 Hz with a lock-in bandwidth chosen to include the noise power of the detector thermal oscillations, which was used for calibration. Each data cycle began with five 120-sample diagnostic runs with a direct-current bias of 5–10 V applied to the shield to induce a large test force, transmitted from source to detector via deflections of the shield. The biased runs were recorded at five drive frequencies separated by 15 mHz to cover the detector resonance. The shield was then grounded and the cycle continued with 720 samples with the drive tuned on-resonance (a, c) and 288 samples with the drive tuned 2 Hz below the detector resonance (b, d). The off-resonance run provided a continuous zero check. A total of 108 such cycles were acquired over five days yielding 77,760 on-resonance samples. The biased diagnostic data show that the source mass amplitude, the detector Q and resonant frequency, and the electronic gain were all stable throughout the data set. [中文](#)

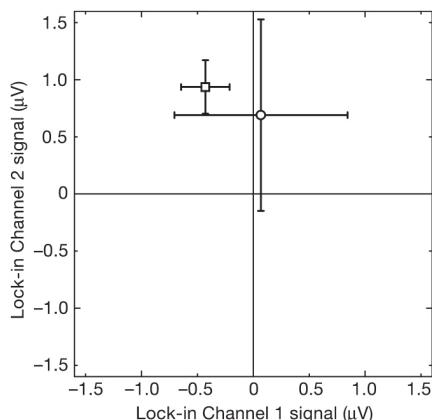


Fig. 3. Means of the off- and on-resonance data samples. The circular point with the larger standard deviations is the on-resonance mean. Correlations between nearby samples have been accounted for in computing the standard deviations shown by error bars. The small

offset from the origin is due to leakage of the reference signal internal to the lock-in. Measurements with the shield removed and a bias voltage between the source and detector show that the phase for an attractive force is 189° . The on-resonance mean minus the off-resonance mean at 189° is $-0.44 \pm 0.82 \mu\text{V}$. Based on calibration via the equipartition theorem this corresponds to a lumped force amplitude at the edge of the detector (smaller rectangle in Fig. 1) of $-1.2 \pm 2.2 \text{ fN}$, where the negative sign indicates repulsion. [中文](#)

Additional cycles of data were acquired with the source mass on the opposite side of the detector, with a larger, 1-mm gap, and with reduced overlap between the source and detector. No resonant signal was observed in any of these sessions, making it unlikely that the observed null result is due to a fortuitous cancellation of surface potential, magnetic, and / or acoustic effects. Several on-resonance runs were acquired with different transducer probe bias voltage settings. The observed linear dependence on bias voltage of the root-mean-square (r.m.s.) fluctuations in these data is consistent with detector motion due only to thermal noise and rules out additional motion from transducer back-action noise. This check is important because the magnitude of the detector thermal motion is used for calibration. [中文](#)

Data from diagnostic runs with a bias voltage applied to the shield can be used to estimate the minimum size of the residual potential difference between the shield and the (grounded) test masses needed to produce a resonant signal. We find that at least 1.5 V would be needed to generate an effect above detector thermal noise, about an order of magnitude larger than the residual potential difference actually measured between the shield and test masses. The most important magnetic background effect involves eddy currents generated when the source mass moves in an external magnetic field. Fields produced by the source currents create eddy currents in the detector, which then interact with the external field. Studies of this effect with large applied magnetic fields show that the ambient field actually present cannot generate a signal greater than one-fifth of the thermal-noise-limited sensitivity. [中文](#)

The instrument can be calibrated in several ways, but the most accurate method is to use the r.m.s. thermal motion of the detector, which dominates the on-resonance distributions in Fig. 2. According to equipartition, the average kinetic energy in each normal mode of the detector is equal to $\frac{1}{2}kT$; where k is Boltzmann's constant and T is the temperature. The normal mode amplitude corresponding to the thermal energy can be calculated, and by comparing this with the observed voltage fluctuations a calibration can be established relating mode amplitude to voltage. A further calculation must be done to find the mode amplitude resulting from any hypothesized force. [中文](#)

For given values of α and λ the driving force due to equation (1) is computed at 30 values of the source mass phase using Monte Carlo integration, and then the Fourier amplitude of the driving force at the resonant frequency is computed. Using the observed statistics of the data we construct a likelihood function for α for each value of λ and compute 95% confidence-level upper limits on α , assuming a uniform prior probability density function (PDF) for α . This analysis is complicated by the presence of uncertainties in the geometrical and mechanical parameters needed to compute the driven displacement. To include these effects we actually construct a likelihood function of α and the uncertain parameters, and then integrate out the uncertain parameters using prior PDFs based on their experimental uncertainties. The most important of these parameters is the 108- μm equilibrium gap between source and detector which has a 6- μm uncertainty. Further details of our analysis methods are given elsewhere¹⁶. [中文](#)

Our results are shown in Fig. 4, together with other experimental limits and the theoretical predictions. Our limit is the strongest available between 10 and 100 μm . When the gluon and strange moduli forces were first proposed, the areas of their allowed regions in the (α, λ) parameter space were 4.4 and 5.2 square decades

respectively. By now they are nearly excluded with only 0.75 and 1.4 square decades still available. Our limit on the dilaton range for $\alpha=2,000$ is $\lambda < 23 \mu\text{m}$ (corresponding to $m > 8.6 \text{ meV}$), a factor of two better than the previous limit. For the radion modulus we set an upper limit on λ of $88 \mu\text{m}$, close to the value of $40 \mu\text{m}$ estimated in the theory (for one extra dimension). For the ADD theory with two large extra compact dimensions, we do not quite reach the limit on the size of these dimensions already set in refs 11 and 12. 中文

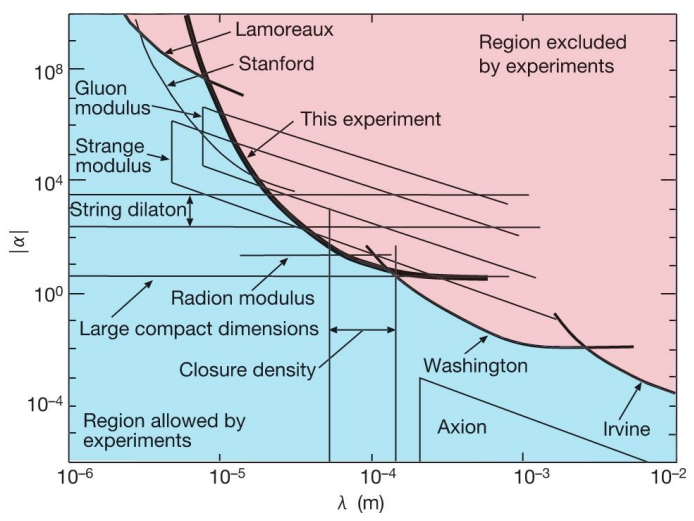


Fig. 4. Current limits on new gravitational strength forces between $1 \mu\text{m}$ and 1 cm . Our result is a 95% confidence-level upper limit on the Yukawa strength α as a function of range λ (solid bold curve). It is shown together with limits from previous experiments (Lamoreaux²⁴, Washington¹², Irvine²⁵) and theoretical predictions newly constrained (gluon modulus⁴, strange modulus⁴, string dilaton², radion modulus⁷). An unpublished limit from the Stanford experiment²⁶ is also shown; it is derived in the presence of a background force. The dilaton strength is somewhat model-dependent and there is a range of values reported in the literature². We have chosen the region $200 < \alpha < 3,000$, which includes most values. Also shown are predictions from the ADD theory with two large compact extra dimensions^{14,27,28}, axion mediated forces^{20,21}, and the λ region corresponding to a cosmological energy density between 1.0 and 0.1 times the closure density¹⁷. For the moduli, dilaton, and ADD theories, the upper bounds on λ of the regions shown are set at the experimental limits that were known at the time the theories were proposed. 中文

Besides forces from extra dimensions, two other ideas have suggested new weak forces at submillimetre scales. The cosmological energy density needed to close the universe, if converted to a length by taking

its inverse fourth root (in natural units where $\hbar=c=1$), corresponds to about 100 μm . This fact has led to repeated attempts¹⁷⁻¹⁹ to address difficulties connected with the very small observed size of Einstein's cosmological constant by introducing new forces with a range near 100 μm . Our result is the best upper bound on α in this region, but we have not quite reached gravitational sensitivity. Finally, the oldest of these predictions, still out of reach, is the very feeble axion-mediated force^{20,21}. The axion is a field intended to explain why the violation of charge-parity symmetry is so small in quantum chromodynamics, the theory of the strong nuclear force. [中文](#)

Experiments of the sort reported here constrain string-inspired scenarios by setting very restrictive limits on predicted submillimetre forces. Of course, the actual observation of any new force would be a major advance. Because several theoretical scenarios point especially to these length scales, it is an important goal for the future to reach gravitational strength at even shorter distances, perhaps down to 10 μm . Experiments attempting to reach such distances will confront rapidly increasing background forces, especially electrostatic forces arising from the spatially non-uniform surface potentials of metals²². Electric fields due to surface potentials can be shielded with good conductors, but because of the finite stiffness of any shield they still cause background forces to be transmitted between test masses. Stretched membranes (as used by the Washington group) are more effective than stiff plates at the shortest distances, but it remains to be seen down to what distance the background forces can be effectively suppressed. [中文](#)

(421, 922-925; 2003)

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References:

1. Greene, B. *The Elegant Universe: Superstrings, Hidden Dimensions, and the Quest for the Ultimate Theory* (Norton, New York, 1999).
2. Kaplan, D. B. & Wise, M. B. Couplings of a light dilaton and violations of the equivalence principle. *J. High Energy Phys.* **8**, 37 (2000).
3. Taylor, T. R. & Veneziano, G. Dilaton couplings at large distances. *Phys. Lett. B* **213**, 450-454 (1988).
4. Dimopoulos, S. & Giudice, G. Macroscopic forces from supersymmetry. *Phys. Lett. B* **379**, 105-114 (1996).
5. Antoniadis, I. A possible new dimension at a few TeV. *Phys. Lett. B* **246**, 377-384 (1990).
6. Antoniadis, I., Dimopoulos, S. & Dvali, G. Millimeter-range forces in superstring theories with weak-scale compactification. *Nucl. Phys. B* **516**, 70-82 (1998).
7. Chacko, Z. & Perazzi, E. Extra dimensions at the weak scale and deviations from Newtonian gravity. Preprint hep-ph / 0210254 available at <arXiv.org> (2002).
8. Fischbach, E. & Talmadge, C. *The Search for Non-Newtonian Gravity* (Springer, New York, 1999).
9. Bordag, M., Mohideen, U. & Mostepanenko, V. M. New Developments in the Casimir effect. *Phys. Rep.* **353**, 1-205 (2001).
10. Long, J. C., Chan, H. W. & Price, J. C. Experimental status of gravitational-strength forces in the sub-centimeter regime. *Nucl. Phys. B* **539**, 23-34 (1999).
11. Hoyle, C. D. *et al.* Sub-millimeter tests of the gravitational inverse-square law: A search for "large" extra dimensions. *Phys. Rev. Lett.* **86**, 1418-1421 (2001).
12. Adelberger, E. G. Sub-mm tests of the gravitational inverse-square law. Preprint hep-ex / 0202008 available at <arXiv.org> (2002).
13. Fischbach, E., Krause, D. E., Mostepanenko, V. M. & Novello, M. New constraints on ultrashort-ranged Yukawa interactions from atomic force microscopy. *Phys. Rev. D* **64**, 075010 (2001).
14. Arkani-Hamed, N., Dimopoulos, S. & Dvali, G. The hierarchy problem and new dimensions at a millimeter. *Phys. Lett. B* **429**, 263-272 (1998).
15. Kleiman, R. N., Kaminsky, G. K., Reppy, J. D., Pindak, R. & Bishop, D. J. Single-crystal silicon high-Q torsional oscillators. *Rev. Sci. Instrum.* **56**, 2088-2091 (1985).
16. Long, J. C. *et al.* New experimental limits on macroscopic forces below 100 microns. Preprint hep-ph / 0210004 available at <arXiv.org> (2002).
17. Beane, S. R. On the importance of testing gravity at distances less than 1 cm. *Gen. Rel. Grav.* **29**, 945-951 (1997).
18. Sundrum, R. Towards an effective particle-string resolution of the cosmological constant problem. *J. High Energy Phys.* **7**, 1 (1999).
19. Schmidhuber, C. Old puzzles. Preprint hep-th / 0207203 available at <arXiv.org> (2002).

20. Moody, J. E. & Wilczek, F. New macroscopic forces? *Phys. Rev. D* **30**, 130-138 (1984).
21. Rosenberg, L. J. & van Bibber, K. A. Searches for invisible axions. *Phys. Rep.* **325**, 1-39 (2000).
22. Price, J. C. in *Proc. Int. Symp. on Experimental Gravitational Physics* (eds Michelson, P., Enke, H. & Pizzella, G.) 436-439 (World Scientific, Singapore, 1988).
23. Chan, H. W., Long, J. C. & Price, J. C. Taber vibration isolator for vacuum and cryogenic applications. *Rev. Sci. Instrum.* **70**, 2742-2750 (1999).
24. Lamoreaux, S. K. Demonstration of the Casimir force in the 0.6 to 6 μm range. *Phys. Rev. Lett.* **78**, 5-8 (1997).
25. Hoskins, J. K., Newman, R. D., Spero, R. & Shultz, J. Experimental tests of the gravitational inverse-square law for mass separations from 2 to 105 cm. *Phys. Rev. D* **32**, 3084-3095 (1985).
26. Chiaverini, J., Smullin, S. J., Geraci, A. A., Weld, D. M. & Kapitulnik, A. New experimental constraints on non-Newtonian forces below 100 microns. Preprint hep-ph / 0209325 available at $\langle \text{arXiv.org} \rangle$ (2002).
27. Floratos, E. G. & Leontaris, G. K. Low scale unification, Newton's law and extra dimensions. *Phys. Lett. B* **465**, 95-100 (1999).
28. Kehagias, A. & Sfetsos, K. Deviations from the $1 / r^2$ Newton law due to extra dimensions. *Phys. Lett. B* **472**, 39-44 (2000).

Acknowledgements. We thank E. Lagae for work in the laboratory, and C. Briggs, T. Buxkemper, L. Czaia, H. Green, S. Gustafson and H. Rohner of the University of Colorado and JILA instrument shops for technical assistance. We also gratefully acknowledge discussions with S. de Alwis, B. Dobrescu and S. Dimopoulos. This work is supported by grants from the US National Science Foundation.

Competing interests statement. The authors declare that they have no competing financial interests.

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来自额外空间维度在亚毫米尺度上力程的上限

朗等

引力是四种基本力中最弱的，比电磁力要小四十个数量级。在弦论——一个试图统一描述粒子和力的尝试——中，引力的弱性是由于引力向着六个额外的卷曲不可见维度泄漏导致的。已经有一些建议说这些卷曲维度的效应可能在很小的尺度下会变得很明显，在这些尺度上物体将会感受到更大的引力。本文中，物理学家乔舒亚·朗和合作者们介绍了一个实验，这个实验在 $100\mu\text{m}$ 的尺度上寻找引力偏离通常熟知的平方反比律的迹象。他们发现没有这样的偏离。

[英文](#)

弦理论是人们一直在寻找的、统一自然界四种力和基本粒子的最有希望的方法^[1]，但是现在仍然缺乏直接支持它的证据。除了我们观察到的三个维度之外，弦理论还要求存在六个额外空间维度。通常假定这些额外的维度卷曲成了很小的空间。这个“紧致化”诱导出了“模”场，用来描述时空中每一点紧致维度的大小和形状。根据最近的预测^[2-7]，这些模场产生了和引力大小可比的力，可能能在 $100\ \mu\text{m}$ 尺度上被探测到。本文中，我们报告了以下工作：用相隔 $108\ \mu\text{m}$ 的两个平面振子来搜寻这一引力强度量级的力。结果未观察到新的力，从而排除了一大块之前对于奇异模力和胶子模力来说是允许的参数空间^[4]，对弦伸缩子力^[2,3]和径向子力^[5-7]的力程给出了一个新的上限。

[英文](#)

由模力和牛顿引力结合得到的势能 V 可以写作

$$V = - \int d\mathbf{r}_1 \int d\mathbf{r}_2 \frac{G\rho_1(\mathbf{r}_1)\rho_2(\mathbf{r}_2)}{r_{12}} [1 + \alpha \exp(-r_{12}/\lambda)] \quad (1)$$

第一项是牛顿万有引力定律， G 是引力常数， r_{12} 是检验质量位置 $\mathbf{r}_1$ 和 $\mathbf{r}_2$ 两点间的距离， ρ_1 ， ρ_2 是两个物体的质量密度。第二项是汤川势， α 是新的力相对于引力的强度， λ 是力程。对于任何传递相互作用的场，模力的力程和它的质量 m 存在如下关系 $\lambda = \hbar / mc$ 。之前关于牛顿引力的检验和对于新的宏观力的搜寻涵盖了从光年到纳米的尺度[8-10]，已有结果表明，在200 μm 到接近一个光年的尺度范围内不存在引力强度量级的新力[8,11,12]，但是在200 μm 之下的尺度，对出现新力的限制会快速变弱（参考文献9和13）。 [英文](#)

奇异模空间和胶子模空间出现在10~100 TeV下超对称（一个弦论中猜想的将玻色子和费米子联系起来的对称性）破缺的时候，而所有的紧致化过程则是发生在临近超高普朗克尺度（ 10^{19} GeV）上的（这些情况下的引力和其他力是统一的）。在这种情况下，可以预测出一个大约是毫米级的力程。伸缩子是弦理论自洽性所要求的一个标量场，它的真空值决定了弦之间相互作用的强度。它或许可以被理解成是M理论中描述第十个空间维度的尺度的模参数，这个空间维度在M理论中被做了紧致化来得到具有九个空间维度的弦论（M理论是将所有不同的弦论整合成一个框架的理论结构^[1]）。和伸缩子相关的强度 α 可以通过计算得到，但是力程 λ 目前只能通过实验来限制，并且我们几乎不知道给出伸缩子质量的机制是什么。径向子是由一个完全不同的机制得到的，这一机制下一个或者多个额外维度的紧致化发生在TeV能标尺度上，但这里实验可以得到的力程 λ 也是预测出来的。 [英文](#)

毫米尺度特殊的重要性可以通过形如 $m \approx M^2 / M_{\text{p}}$ 的质量公式导出，这里 M_{p} 是和普朗克尺度相关的质量 10^{19} GeV / c^2 ， M 是1~100 TeV / c^2 的质量，导致 λ 的尺度在厘米到微米范围之间。在奇异模空间和胶子模空间中， M 是超对称破缺发生的尺度，而在径向子模空间的情况下，它对应于一个或者多个紧致维度的尺度。这个公式适用于ADD理论^[14]（根据其提出者们的姓名命名），这一理论中两个毫米尺度的紧致化额外维会修改引力。在ADD理论中， M 是一个基本尺度，在这个尺度上所有的物理理论都是统一起来的，而 m 是对应于大的紧致化额外维尺度的

质量。在许多紧致化图像中，对称性破缺和质量产生依然是可靠的，因此，尽管在毫米尺度上观察到新力的可能性是令人激动的，但这些实验目前还不能证伪弦理论。 英文

我们选择的源和探测器质量呈现为图1所示的平面几何，是为了使其尽可能地在感兴趣的尺度上集中更高的质量密度。它几乎不受 $1/r^2$ 牛顿背景的影响，这在寻找一个新力的时候是一个有帮助的特征。钨制的源的悬臂模式（和跳水板的运动类似）在探测器共振频率的驱动下出现了19 μm 的尖端振幅。钨探测器是双扭转振子^[15]，在我们感兴趣的共振模式下，探测器的两个矩形部分绕着扭转轴反转，绝大部分振幅都被限制在防护屏和源下面的小矩形中。如果源和探测器之间存在一个质量耦合力的话将会驱动探测器的扭转运动。运动用电容传感器探测，跟着是一个前置放大器、过滤器和锁定放大器。为了压低由于静电和剩余气体产生的背景力，一个刚性的导电防护屏固定在两个检验质量之间。对于静止的源，源和探测器的距离调整到108 μm ，整个仪器放在真空罩中，然后将压强控制在 2×10^{-7} torr以下。 英文

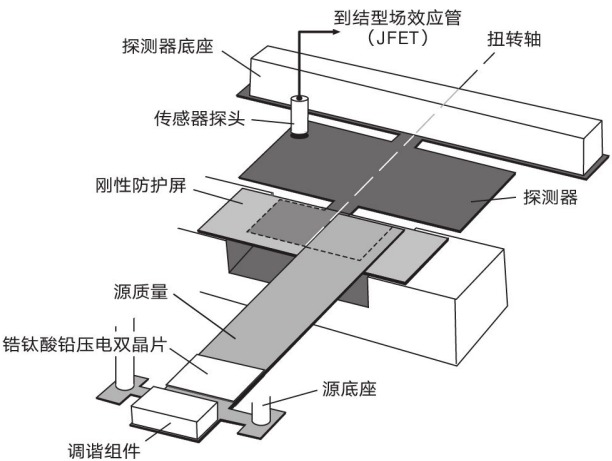


图1．仪器的主要构成。钨探测器的小矩形（在防护屏下面）有11.455 mm宽，5.080 mm长，195 μm 厚。探测器在1,300 $^{\circ}\text{C}$ 下退火以便增加它的机械品质因子Q到25,000。在操作上，探测器1,173.085 Hz的共振频率是通过主动地将探测器的温度控制在305 K来稳定下来。钨制的源有35 mm长，7 mm宽，305 μm 厚。源的共振频率调制到探测器的共振频率，并由锆钛酸铅（PZT）压电双晶片驱动。防护屏是一个60 μm 厚的蓝宝石板，两侧镀上了100 nm厚的金。检验质量和防护屏由三个分立的五步被动隔振层支撑^[23]，每一个在1 kHz时提供了大约200 dB的噪音减弱。机械探头用来直接探测每个组分的相对取向和位置，还用来测量源的振幅。探测器的运动通过在探测器大矩形后面的角的上方100 μm 处的一个圆柱形电容式探头来感知。探头通过一个100 G Ω 的电阻在200 V电压上偏置，并且通过一个隔直流电容器连着一个SK 152的结型

场效应晶体管（JFET）。JFET 100 mK的噪声温度足够用来探测305 K的探测器的热运动了。JFET前置放大器接着第二个前置放大器、过滤器，最后是一个两相锁定放大器。从电容式探头到锁定放大器输入的总电压放大了约1,600倍。一个晶体调制的振子给锁定放大器提供了一个参考信号，并且通过一个1：10的升压变压器驱动源质量的PZT。[英文](#)

图2展示了原始数据的直方图，当源的驱动频率在探测器的共振频率时和不在探测器的共振频率时都收集了数据。每个图都包含来自锁定放大器的一个通道的信号，对应于在驱动频率下探测器运动两个正交模式中的一个。非共振分布的展宽是因为前置放大器的噪声，而共振分布的展宽来自前置放大器的噪声和探测器的热运动之和。图3中这个共振和非共振的平均值在标准偏差之内是吻合的，表明不存在一个显著的共振力的信号。[英文](#)

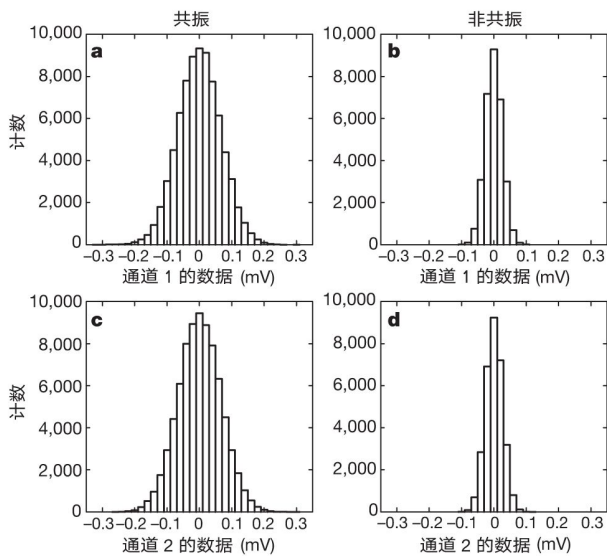


图2．数据样本的分布。数据在1 Hz处收集，选取的锁定带宽包含了探测器热振动的噪声功率以用于校正。每个数据周期从120个样本的5次诊断运行开始，在防护屏上应用5~10 V的直流偏压，用来产生一个很大的检测力，然后通过防护屏的偏转在源到探测器之间传递。偏置运行在五个驱动频率下记录，这五个驱动频率之间间隔15 mHz从而覆盖探测器共振频率。防护屏之后接地，然后这个周期继续在驱动频率调到共振频率的720个样本（a和c）和驱动频率调到探测器共振频率以下2 Hz处的288个的样本（b和d）中进行。非共振运行提供了一个连续的零检验。五天时间内获得了共108个这样的循环，产生了77,760个共振样本。偏置诊断的数据显示源质量的振幅、探测器的品质因子Q和共振频率以及电子增益在整个数据集上都是稳定的。[英文](#)

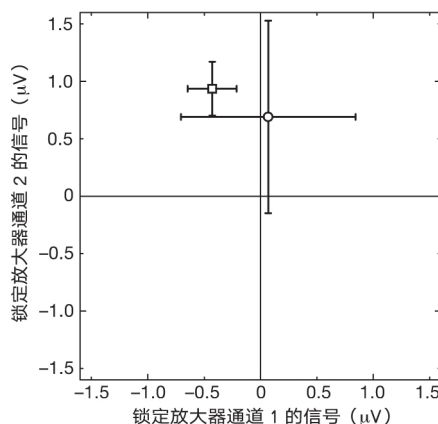


图3．非共振和共振数据样本的平均值。具有更大标准偏差的圆点是共振的平均值。邻近样本之间的关联在计算标准偏差时已经考虑进去了，标准偏差用误差棒来体现。原点处的微小偏移来源于锁定放大器内部的参考信号的溢出。去掉防护屏，并在源和探测器之间加上偏置电压进行了探测，结果显示吸引力的相位是 189° 。在 189° ，共振的平均值减去非共振的平均值是 $-0.44 \pm 0.82 \mu\text{V}$ 。基于通过能均分定理的校正，这对应于一个在探测器边缘（图1中的小矩形）大小为 $-1.2 \pm 2.2 \text{ fN}$ 的集总力振幅，负号表明它是排斥力。 [英文](#)

更多的数据周期通过将源放在探测器的另外一侧获得，源和探测器之间有一个比之前大的、大小为 1 mm 的间隙，并且有着更小的交叠。在这些测量中都没有看到任何的共振信号，使得观测到的零结果不太可能源于表面势、磁和（或）声学效应的偶然抵消。设定不同的传感器探头的偏置电压获得了几次共振。在这些数据中观测到的方均根误差的涨落对于偏置电压的线性依赖和只由热噪声产生的探测器运动是自洽的，排除了传感器反作用噪声导致的额外运动。这个检查是重要的，因为探测器热运动的大小是被用来做校正的。 [英文](#)

来自诊断运行（在防护屏上施加偏置电压）的数据可以用来估计防护屏和（接地的）检验质量之间的剩余电势差的最小尺度，这个电势差是需要的，它可以产生一个共振信号。我们发现至少需要 1.5 V 的电压来产生一个高于探测器热噪声的效应， 1.5 V 大约比测得的在防护屏和检验质量之间的剩余电势差高一个数量级。最重要的磁背景效应是当源在外磁场运动时产生的涡流。源电流产生的场在探测器中产生了涡流，涡流之后会和外部的场相互作用。关于这个大施加磁场带来的效应的研究表明，周围实际存在的场所产生的信号，不能大于热噪声限制给出的灵敏度的五分之一。 [英文](#)

这个实验器材可以通过几种方式校正，但是最准确的方法是用探测器的方均根热运动进行校正，它在图2的共振分布中占主导。根据能均分定理，每个探测器正则模式的平均动能等于 $\frac{1}{2}kT$ ； k 是玻尔兹曼常数而 T 是温度。对应于热能的正则模式的振幅可以算出来，比较它和观测到的电压涨落，可以通过将模式振幅和电压联系起来建立一个校正。如果要寻找任何假设存在的力所产生的模式振幅，需要进行更进一步的计算。

[英文](#)

对于给定的 α 和 λ 的值，由方程（1）给出的驱动力在源相位取的30个值下用蒙特卡罗积分计算，然后算出驱动力在共振频率下的傅里叶振幅。用观测到的数据统计，我们对每个 λ 的值构建了一个 α 的似然函数，然后在假定了一个 α 的均匀先验概率密度分布函数（PDF）的基础上，在95%的置信度上计算了 α 的上限。由于计算驱动位移时所需要的几何和动力学参数存在不确定性，这个分析会变得复杂。为了包括这些效应，我们实际上构建了一个 α 和这些不确定参数的似然函数，然后基于实验不确定性，利用先验概率密度分布函数积掉了不确定的参数。这些参数中最重要的是在源和探测器之间具有6 μm 不确定性的108 μm 平衡间隙。分析方法的进一步细节在其他论文中给出^[16]。

[英文](#)

图4展示了我们的结果，其中也包括其他实验的限制和理论的预言。我们的限制在10 μm 到100 μm 范围内是已知的方法中最强的。当胶子模力和奇异模力第一次被提出的时候，它们在 (α, λ) 参数空间中所允许的区域分别是4.4和5.2个单位。现在它们除了0.75和1.4个允许的单位外，其余的都被排除了。关于 $\alpha=2,000$ 的伸缩子的范围，我们的限制是 $\lambda < 23 \mu\text{m}$ （对应于 $m > 8.6 \text{ MeV}$ ），比之前的极限好上一倍。对于径向子的模空间，我们给出了一个 $\lambda=88 \mu\text{m}$ 的上限，接近理论（一个额外维）预言的40 μm 的值。对于有两个大的额外紧致维度的ADD理论，我们并没有达到文献11和12中给出的关于这些维度的大小的极限。

[英文](#)

[英文](#)

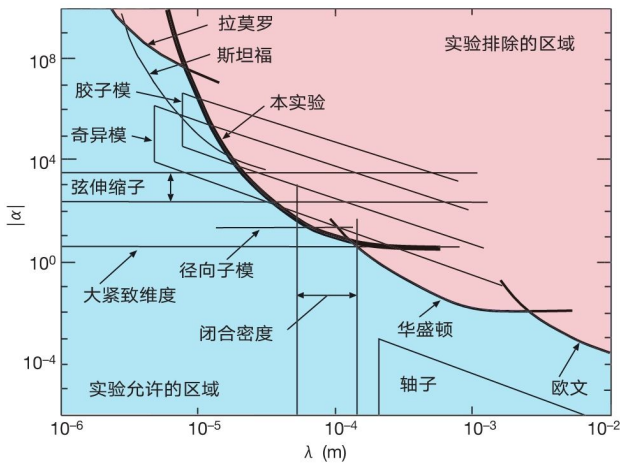


图4：目前1 μm 到1 cm之间的新引力强度的限制。我们的结果是一个在95%置信度上汤川强度 α 函数的上限，它是关于力程 λ 的函数（粗体实线）。之前的实验（拉莫罗[24]，华盛顿[12]，欧文[25]）给出的极限以及理论预言给出的新极限也一并展示在图中（胶子模[4]，奇异模[4]，弦伸缩子[2]，径向子模[7]）。一个来自斯坦福的未发表的实验[26]也展示在图中，它是在存在背景力的前提下得到的。伸缩子的强度某种意义上是依赖于模型，在文献中有一个取值范围[2]。我们选择区域 $200 < \alpha < 3,000$ ，它包含了大部分的值。图中也展示了分别由具有两个大的紧致额外维度的ADD理论[14,27,28]，轴子传递的力[20,21]以及宇宙学能量密度在1.0到0.1倍闭合能量密度之间的 λ 区域[17]所给出的预言结果。对于模空间、伸缩子和ADD理论，展示的 λ 区域的上界设置在理论提出时人们已知的实验所能达到的极限。 [英文](#)

除了来自额外维的力，还有其他两个想法可以在亚毫米尺度给出新的弱的相互作用。用来闭合宇宙的宇宙学（临界）能量密度，如果通过做它的负四次方根来得到一个长度（在自然单位制下 $\hbar=c=1$ ），结果大概是100 μm 。这个事实使得人们不断尝试[17-19]通过引入一个力程大约100 μm 的力来解决爱因斯坦的宇宙学常数的观测值很小所带来的困难。我们的结果是这个区域内能得到的最好的上界，但是我们还没有达到引力的灵敏度。最后，这些预言中最古老的一个，也是目前依然探测不到的，是很微弱的轴子传递的相互作用[20,21]。轴子的引入是为了解释为什么在量子色动力学（强核力的理论）中电荷-宇称对称性的破缺是如此的微小。 [英文](#)

本文报道的这类实验对预测在亚毫米尺度上存在额外力的类弦理论给出了一个很强约束性的极限。当然，能够观测到任何新的力都将是一个巨大的进步。因为一些理论特别地指向了这些尺度，未来在更小的距离（可能低至10 μm 以下）上到达引力的强度将是一个重要的目标。试图到达这个距离的实验将会面临更快速增长的背景力，尤其是由于金属

表面空间不均匀的势所产生的静电力^[22]。表面势产生的电场可以被良导体屏蔽，但是由于任何防护屏都有有限的刚性系数，它们依然会造成表面力在检验质量之间传递。延展的膜（即华盛顿课题组所使用的材料）在小距离下比刚性的盘更加有效，但是低至多大的距离下背景力可以被有效地压低还不能确定。 [英文](#)

（安宇森 翻译；蔡荣根 审稿）

A Precision Measurement of the Mass of the Top Quark

DØ Collaboration*

Although the standard model of particle physics is extremely successful, it does not in itself explain the masses of subatomic particles. Instead, they are hypothesized to arise from the interactions of particles with the so-called Higgs boson. Here an international team called the DØ collaboration, working at the Tevatron supercollider at Fermilab in Illinois, report a high-precision measurement of the mass of the top quark, which helps to constrain the range of allowable masses for the Higgs boson. The results suggest that it is more massive than was previously thought, so that more energy will be required to make it. The Higgs boson was finally observed in the Large Hadron Collider at CERN in Geneva in 2012. Its mass is lighter than was expected. 中

文

The standard model of particle physics contains parameters—such as particle masses—whose origins are still unknown and which cannot be predicted, but whose values are constrained through their interactions. In particular, the masses of the top quark (M_t) and W boson (M_W)¹ constrain the mass of the long-hypothesized, but thus far not observed, Higgs boson. A precise measurement of M_t can therefore indicate where to look for the Higgs, and indeed whether the hypothesis of a standard model Higgs is consistent with

experimental data. As top quarks are produced in pairs and decay in only about 10^{-24} s into various final states, reconstructing their masses from their decay products is very challenging. Here we report a technique that extracts more information from each top-quark event and yields a greatly improved precision (of ± 5.3 GeV / c^2) when compared to previous measurements². When our new result is combined with our published measurement in a complementary decay mode³ and with the only other measurements available², the new world average for M_t becomes⁴ 178.0 ± 4.3 GeV / c^2 . As a result, the most likely Higgs mass increases from the experimentally excluded⁵ value⁶ of 96 to 117 GeV / c^2 , which is beyond current experimental sensitivity. The upper limit on the Higgs mass at the 95% confidence level is raised from 219 to 251 GeV / c^2 . [中文](#)

THE discovery of the top quark in 1995 served as one of the major confirmations of the validity of the standard model (SM)^{7,8}. Of its many parameters, the mass of the top quark, in particular, reflects some of the most crucial aspects of the SM. This is because, in principle, the top quark is point-like and should be massless; yet, through its interactions with the hypothesized Higgs field, the physical mass of the top quark appears to be about the mass of a gold nucleus. Because it is so heavy, the top quark (along with the W boson) provides an unusually sensitive tool for investigating the Higgs field. M_W is known to a precision of 0.05%, while the uncertainty on M_t is at the 3% level¹. Improvements in both measurements are required to restrict further the allowed range of mass for the Higgs; however, given the large uncertainty in M_t , an improvement in its precision is particularly important. As has been pointed out recently^{9,10}, a potential problem for the SM is that, on the basis of the currently accepted value for M_t , the most likely value of the Higgs mass⁶ lies in a range that has already been excluded by experiment⁵. Precise

knowledge of the Higgs mass is crucial for our understanding of the SM and any possible new physics beyond it. For example, in a large class of supersymmetric models (theoretically preferred solutions to the deficiencies of the SM), the Higgs mass has to be less than about $135 \text{ GeV} / c^2$. Although, unlike the SM, supersymmetry predicts more than one Higgs boson, the properties of the lightest one are expected to be essentially the same as those for the SM Higgs boson. Thus, if the SM-like Higgs is heavier than about $135 \text{ GeV} / c^2$, it would disfavour a large class of supersymmetric models. In addition, some of the current limits on supersymmetric particles from LEP¹¹ are extremely sensitive to M_t . In fact, for M_t greater than $179 \text{ GeV} / c^2$, the bounds on one of the major supersymmetry parameters, $\tan\beta$, which relates the properties of the SM-like Higgs boson and its heavier partners, would disappear completely¹². Hence, in addition to the impact on searches for the Higgs boson, other important consequences call for improved precision on M_t , and this goal is the main subject of this paper. 中

文

The $D\bar{O}$ experiment at the Fermilab Tevatron has studied a sample of $t\bar{t}$ events produced in proton–antiproton ($p\bar{p}$) interactions¹³. The total energy of 1.8 TeV released in a head-on collision of a 900-GeV p and a 900-GeV $\bar{p}$ is almost as large as the rest energy of ten gold nuclei. Each top (antitop) quark decays almost immediately into a bottom ($\bar{b}$) quark and a W^+ (W^-) boson, and we have reexamined those events in which one of the W bosons decays into a charged lepton (electron or muon) and a neutrino, and the other W into a quark and an antiquark (see Fig. 1). These events and their selection criteria are identical to those used to extract the mass of the top quark in our previous publication, and correspond to an integrated luminosity of 125 events per pb. (That is, given the production cross-section of the $t\bar{t}$ in $p\bar{p}$ collisions at 1.8 TeV of 5.7 pb, as measured by $D\bar{O}$ ¹⁴, these data correspond to approximately 700 produced $t\bar{t}$ pairs, a fraction of which is fully detected in various possible decay modes.

Approximately 30% of these correspond to the lepton + jets topology categorized in Fig. 2, where “jet” refers to products of the fragmentation of a quark into a collimated group of particles that are emitted along the quark’s original direction.) The main background processes correspond to multijet production (20%), where one of the jets is reconstructed incorrectly as a lepton, and the $W + \text{jets}$ production with leptonic W decays (80%), which has the same topology as the $t\bar{t}$ signal. 中文

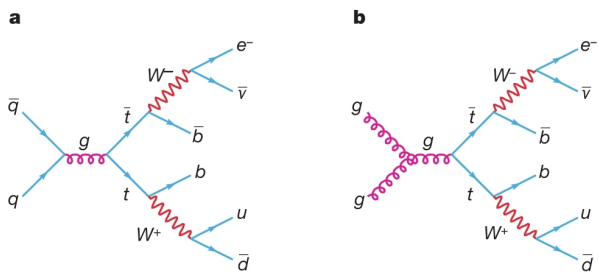


Fig. 1. Feynman diagrams for $t\bar{t}$ production in $p\bar{p}$ collisions, with subsequent decays into an electron, neutrino, and quarks. Quark–antiquark production (a) is dominant, but gluon fusion (b) contributes $\sim 10\%$ to the cross-section. This particular final state ($e\nu u\bar{d}b\bar{b}$) is one of the channels used in the analysis. 中文

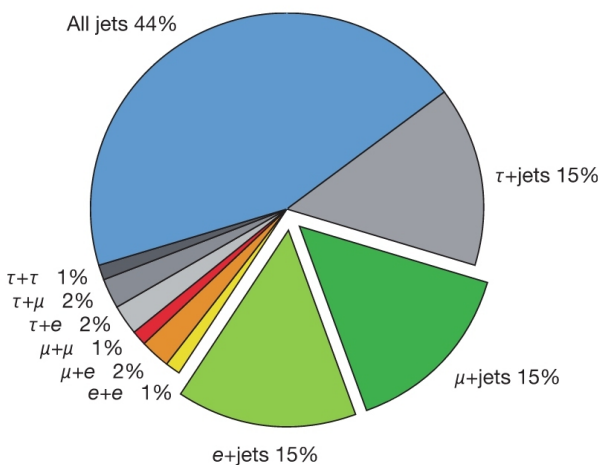


Fig. 2. Relative importance of various $t\bar{t}$ decay modes. The “lepton + jets” channel used in this analysis corresponds to the two offset slices of the pie-chart and amounts to 30% of all the $t\bar{t}$ decays 中文

The previous $D\bar{0}$ measurement of M_t in this lepton + jets channel is

$M_t = 173.3 \pm 5.6$ (stat) ± 5.5 (syst) GeV / c^2 , and is based on 91 candidate events. Information pertaining to the older analysis and the DØ detector can be found elsewhere^{13,15}. [中文](#)

The new method of M_t measurement is similar to one suggested previously (ref. 16 and references therein, and ref. 17) for $t\bar{t}$ dilepton decay channels (where both W bosons decay leptonically), and used in previous mass analyses of dilepton events³, and akin to an approach suggested for the measurement of the mass of the W boson at LEP¹⁸⁻²⁰. The critical differences from previous analyses in the lepton + jets decay channel lie in: (1) the assignment of more weight to events that are well measured or more likely to correspond to $t\bar{t}$ signal, and (2) the handling of the combinations of final-state objects (lepton, jets and imbalance in transverse momentum, the latter being a signature for an undetected neutrino) and their identification with top-quark decay products in an event (such as from ambiguity in choosing jets that correspond to b or $\bar{b}$ quarks from the decays of the t and $\bar{t}$ quarks). Also, because leading-order matrix elements were used to calculate the event weights, only events with exactly four jets are kept in this analysis, resulting in a candidate sample of 71 events. Although we are left with fewer events, the new method for extracting M_t provides substantial improvement in both statistical and systematic uncertainties. [中文](#)

We calculate as a function of M_t the differential probability that the measured variables in any event correspond to signal. The maximum of the product of these individual event probabilities provides the best estimate of M_t in the data sample. The impact of biases from imperfections in the detector and event-reconstruction algorithms is taken into account in two ways. Geometric acceptance, trigger efficiencies, event selection, and so on enter through a multiplicative acceptance function that is independent of M_t . Because the angular directions of all the objects in the event, as well as the electron

momentum, are measured with high precision, their measured values are used directly in the calculation of the probability that any event corresponds to $t\bar{t}$ or background production. The known momentum resolution is used to account for uncertainties in measurements of jet energies and muon momenta. [中文](#)

As in the previous analysis¹³, momentum conservation in $\gamma + \text{jet}$ events is used to check that the energies of jets in the experiment agree with Monte Carlo (MC) simulations. This calibration has an uncertainty $\delta E = (0.025E + 0.5 \text{ GeV})$. Consequently, all jet energies in our sample are rescaled by $\pm \delta E$, the analysis redone, and half of the difference in the two rescaled results for M_t ($\delta M_t = 3.3 \text{ GeV} / c^2$) is taken as a systematic uncertainty from this source. All other contributions to systematic uncertainty: MC modelling of signal ($\delta M_t = 1.1 \text{ GeV} / c^2$) and background ($\delta M_t = 1.0 \text{ GeV} / c^2$), effect of calorimeter noise and event pile-up ($\delta M_t = 1.3 \text{ GeV} / c^2$), and other corrections from M_t extraction ($\delta M_t = 0.6 \text{ GeV} / c^2$) are much smaller, and discussed in detail elsewhere^{21,22}. It should be noted that the new mass measurement method provides a significant (about 40%, from ± 5.5 to $\pm 3.9 \text{ GeV} / c^2$) reduction in systematic uncertainty, which is ultimately dominated by the measurement of jet energies. For details on the new analysis, see the Methods. [中文](#)

The final result is $M_t = 180.1 \pm 3.6 \text{ (stat)} \pm 3.9 \text{ (syst)} \text{ GeV} / c^2$. The improvement in statistical uncertainty over our previous measurement is equivalent to collecting a factor of 2.4 as much data. Combining the statistical and systematic uncertainties in quadrature, we obtain $M_t = 180.1 \pm 5.3 \text{ GeV} / c^2$, which is consistent with our previous measurement in the same channel (at about 1.4 standard deviations), and has a precision comparable to all previous M_t measurements combined¹. [中文](#)

The new measurement can be combined with that obtained for the dilepton sample that was also collected at DØ during run I (ref. 3)

($M_t = 168.4 \pm 12.3$ (stat) ± 3.6 (syst) GeV / c^2), to yield the new DØ average for the mass of the top quark:

$$M_t = 179.0 \pm 5.1 \text{ GeV}/c^2 \quad (1)$$

Combining this with measurements from the CDF experiment² provides a new “world average” (based on all measurements available) for the mass of the top quark⁴:

$$M_t = 178.0 \pm 4.3 \text{ GeV}/c^2 \quad (2)$$

dominated by our new measurement. This new world average shifts the best-fit value of the expected Higgs mass from 96 GeV / c^2 to 117 GeV / c^2 (see Fig. 3), which is now outside the experimentally excluded region, yet accessible in the current run of the Tevatron and at future runs at the Large Hadron Collider (LHC), at present under construction at CERN. (The upper limit on the Higgs mass at the 95% confidence level changes from 219 GeV / c^2 to 251 GeV / c^2 .) Figure 3 shows the effect of using only the new DØ top mass for fits to the Higgs mass, and indicates a best value of 123 GeV / c^2 and the upper limit of 277 GeV / c^2 at the 95% confidence level. It should be noted that the horizontal scale in Fig. 3 is logarithmic, and the limits on the Higgs boson mass are therefore asymmetric. [中文](#)

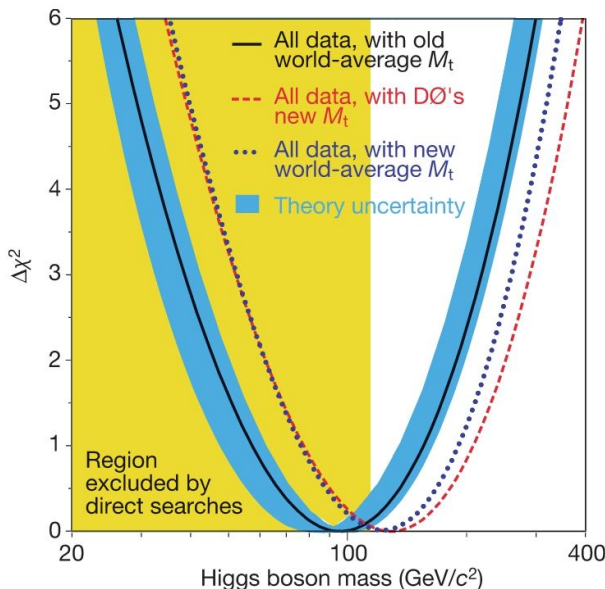


Fig. 3. Current experimental constraints on the mass of the Higgs boson. The χ^2 for a global fit to electroweak data⁶ is shown as a function of the Higgs mass. The solid line corresponds to the result for the previous world-averaged $M_t = 174.3 \pm 5.1 \text{ GeV} / c^2$, with the blue band indicating the impact of theoretical uncertainty. The dotted line shows the result for the new world-average M_t of $178.0 \pm 4.3 \text{ GeV} / c^2$, whereas the dashed line corresponds to using only the new DØ average of $179.0 \pm 5.1 \text{ GeV} / c^2$. The yellow-shaded area on the left indicates the region of Higgs masses excluded by experiment ($> 114.4 \text{ GeV} / c^2$ at the 95% confidence level⁵). The improved M_t measurement shifts the most likely value of the Higgs mass above the experimentally excluded range. [中文](#)

The new method is already being applied to data being collected by the CDF and DØ experiments at the new run of the Fermilab Tevatron and should provide even higher precision on the determination of M_t , equivalent to more than a doubling of the data sample, relative to using the conventional method. An ultimate precision of about $2 \text{ GeV} / c^2$ on the mass of the top quark is expected to be reached in several years of Tevatron operation. Further improvement may eventually come from the LHC. [中文](#)

Methods

The probability density as a function of M_t can be written as a convolution of the calculable cross-section and any effects from

measurement resolution

$$P(x, M_t) = \frac{1}{\sigma(M_t)} \int d\sigma(y, M_t) dq_1 dq_2 f(q_1) f(q_2) W(y, x) \quad (3)$$

where $W(y, x)$, our general transfer function, is the normalized probability for the measured set of variables x to arise from a set of nascent (partonic) variables y , $d\sigma(y, M_t)$ is the partonic theoretical differential cross-section, $f(q)$ are parton distribution functions that reflect the probability of finding any specific interacting quark (antiquark) with momentum q within the proton (antiproton), and $\sigma(M_t)$ is the total cross-section for producing $t\bar{t}$. The integral in equation (3) sums over all possible parton states, leading to what is observed in the detector. 中文

The acceptance of the detector is given in terms of a function $A(x)$ that relates the probability $P_m(x, M_t)$ of measuring the observed variables x to their production probability $P(x, M_t)$: $P_m(x, M_t) = A(x)P(x, M_t)$. Effects from energy resolution, and so on are taken into account in the transfer function $W(y, x)$. The integrations in equation (3) over the eleven well-measured variables (three components of charged-lepton momentum and eight jet angles) and the four equations of energy-momentum conservation leave five integrals that must be performed to obtain the probability that any event represents $t\bar{t}$ (or background) production for some specified value of M_t . 中文

The probability for a $t\bar{t}$ interpretation can be written as:

$$P_{t\bar{t}} = \frac{1}{12\sigma_{t\bar{t}}} \int d^5\Omega \sum_{\text{perm., } \nu} |M_{t\bar{t}}|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \Phi_6 W_{\text{jets}}(E_{\text{part}}, E_{\text{jet}})$$

where Ω represent a set of five integration variables, $M_{t\bar{t}}$ is the leading-order matrix element for $t\bar{t}$ production^{23,24}, $f(q_1)$ and $f(q_2)$ are the CTEQ4M parton distribution functions for the incident quarks²⁵,

Φ_6 is the phase-space factor for the six-object final state, and the sum is over all 12 permutations of the jets and all possible neutrino solutions. $W_{\text{jets}}(E_{\text{part}}, E_{\text{jet}})$ corresponds to a function that maps parton-level energies E_{part} to energies measured in the detector E_{jet} and is based on MC studies. A similar expression, using a matrix element for W +jets production (the dominant background source) that is independent of M_t , is used to calculate the probability for a background interpretation, P_{bkg} . 中文

Studies of samples of HERWIG (ref. 26; we used version 5.1) MC events indicate that the new method is capable of providing almost a factor-of-two reduction in the statistical uncertainty on the extracted M_t . These studies also reveal that there is a systematic shift in the extracted M_t that depends on the amount of background there is in the data. To minimize this effect, a selection is introduced, based on the probability that an event represents background. The specific value of the P_{bkg} cut-off is based on MC studies carried out before applying the method to data, and, for $M_t = 175 \text{ GeV} / c^2$, retains 71% of the signal and 30% of the background. A total of 22 data events out of our 71 candidates pass this selection. 中文

The final likelihood as a function of M_t is written as:

$$\ln L(M_t) = \sum_{i=1}^n \ln [c_1 P_{\text{sig}}(x_i, M_t) + c_2 P_{\text{bkg}}(x_i)] - N \int A(x) [c_1 P_{\text{sig}}(x, M_t) + c_2 P_{\text{bkg}}(x)] dx$$

The integration is performed using MC methods. The best value of M_t (when L is at its maximum L_{max}) represents the most likely mass of the top quark in the final N -event sample, and the parameters c_i reflect the amounts of signal and background. MC studies show that there is a downward shift of $0.5 \text{ GeV} / c^2$ in the extracted mass, and this correction is applied to the result. Reasonable changes in the cut-off on P_{bkg} do not have a significant impact on M_t . 中文

Figure 4 shows the value of $L(M_t) / L_{\text{max}}$ as a function of M_t for the 22

events that pass all selection criteria, after correction for the $0.5 \text{ GeV} / c^2$ bias in mass. The likelihood is maximized with respect to the parameters c_i at each mass point. The gaussian fit in the figure yields $M_t = 180.1 \text{ GeV} / c^2$, with a statistical uncertainty of $\delta M_t = 3.6 \text{ GeV} / c^2$. The systematic uncertainty, dominated by the measurement of jet energies, as discussed above, amounts to $\delta M_t = 3.9 \text{ GeV} / c^2$. When added in quadrature to the statistical uncertainty from the fit, it yields the overall uncertainty on the new M_t measurement of $\pm 5.3 \text{ GeV} / c^2$.

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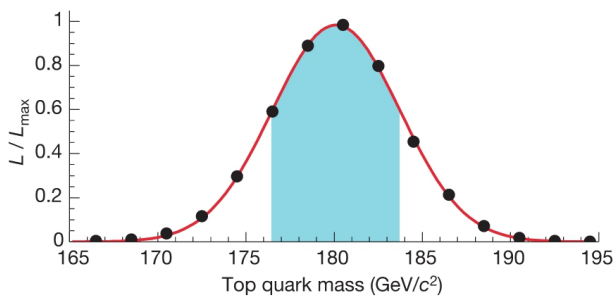


Fig. 4. Determination of the mass of the top quark using the maximum-likelihood method. The points represent the likelihood of the fit used to extract M_t divided by its maximum value, as a function of M_t (after a correction for a $-0.5 \text{ GeV} / c^2$ mass bias, see text). The solid line shows a gaussian fit to the points. The maximum likelihood corresponds to a mass of $180.1 \text{ GeV} / c^2$, which is the new $D\bar{O}$ measurement of M_t in the lepton+jets channel. The shaded band corresponds to the range of ± 1 standard deviation, and indicates the $\pm 3.6 \text{ GeV} / c^2$ statistical uncertainty of the fit.

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(429, 638-642; 2004)

Received 23 January; accepted 21 April 2004; doi:10.1038 / nature02589.

References:

1. Hagiwara, K. *et al.* Review of particle physics. *Phys. Rev. D* **66**, 010001 (2002).
2. Affolder, T. *et al.* (CDF Collaboration). Measurement of the top quark mass with the Collider Detector at Fermilab. *Phys. Rev. D* **63**, 032003 (2001).
3. Abbott, B. *et al.* ($D\bar{O}$ Collaboration). Measurement of the top quark mass in the dilepton channel. *Phys. Rev. D* **60**, 052001 (1999).
4. The CDF Collaboration, the $D\bar{O}$ Collaboration, and the TEVATRON Electro-Weak Working Group. Combination of CDF and $D\bar{O}$ Results on the Top-Quark Mass. Preprint at <http://www.arXiv.org> / hep-ex / 0404010 (2004).

5. Barate, R. *et al.* (ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, and LEP Working Group for Higgs boson searches). Search for the standard model Higgs boson at LEP. *Phys. Lett. B* **565**, 61-75 (2003).
6. The LEP Collaborations ALEPH, DELPHI, L3, and OPAL, the LEP Electroweak Working Group, and the SLD Heavy Flavour Group. A combination of preliminary electroweak measurements and constraints on the standard model. Preprint at <http://www.arXiv.org/hep-ex/0312023> (2003).
7. Abe, F. *et al.* (CDF Collaboration). Observation of top quark production in $p\bar{p}$ collisions with the Collider Detector at Fermilab. *Phys. Rev. Lett.* **74**, 2626-2631 (1995).
8. Abachi, S. *et al.* (DØ Collaboration). Observation of the top quark. *Phys. Rev. Lett.* **74**, 2632-2637 (1995).
9. Ellis, J. The 115 GeV Higgs odyssey. *Comments Nucl. Part. Phys. A* **2**, 89-103 (2002).
10. Chanowitz, M. S. Electroweak data and the Higgs boson mass: a case for new physics. *Phys. Rev. D* **66**, 073002 (2002).
11. The LEP Collaborations ALEPH, DELPHI, L3 & OPAL, the LEP Higgs Working Group. Searches for the neutral Higgs bosons of the MSSM: preliminary combined results using LEP data collected at energies up to 209 GeV. Preprint at <http://www.arXiv.org/hep-ex/0107030> (2001).
12. Degrassi, G., Heinemeyer, S., Hollik, W., Slavich, P. & Weiglein, G. Towards high-precision predictions for the MSSM Higgs sector. *Eur. Phys. J. C* **28**, 133-143 (2003).
13. Abbott, B. *et al.* (DØ Collaboration). Direct measurement of the top quark mass by the DØ collaboration. *Phys. Rev. D* **58**, 052001 (1998).
14. Abazov, V. M. *et al.* (DØ Collaboration). $t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. *Phys. Rev. D* **67**, 012004 (2003).
15. Abachi, S. *et al.* (DØ Collaboration). The DØ detector. *Nucl. Instrum. Methods A* **338**, 185-253 (1994).
16. Dalitz, R. H. & Goldstein, G. R. Test of analysis method for top-antitop production and decay events. *Proc. R. Soc. Lond. A* **445**, 2803-2834 (1999).
17. Kondo, K. *et al.* Dynamical likelihood method for reconstruction of events with missing momentum. 3: Analysis of a CDF high p_T $e\mu$ event as $t\bar{t}$ production. *J. Phys. Soc. Jpn* **62**, 1177-1182(1993).
18. Berends, F. A., Papadopoulos, C. G. & Pittau, R. On the determination of M_W and TGCs in W -pair production using the best measured kinematical variables. *Phys. Lett. B* **417**, 385-389 (1998).
19. Abreu, P. *et al.* (DELPHI Collaboration). Measurement of the W pair cross-section and of the W Mass in e^+e^- interactions at 172 GeV. *Eur. Phys. J. C* **2**, 581-595 (1998).
20. Juste, A. Measurement of the W mass in e^+e^- annihilation PhD thesis, 1-160, Univ. Autonoma de Barcelona (1998).
21. Estrada, J. Maximal use of kinematic information for extracting the top quark mass in single-lepton $t\bar{t}$ events PhD thesis, 1-132, Univ. Rochester (2001).
22. Canelli, F. Helicity of the W boson in single-lepton $t\bar{t}$ events PhD thesis. 1-241, Univ. Rochester (2003).
23. Mahlon, G. & Parke, S. Angular correlations in top quark pair production and decay at hadron colliders. *Phys. Rev. D* **53**, 4886-4896 (1996).

24. Mahlon, G. & Parke, S. Maximizing spin correlations in top quark pair production at the Tevatron. *Phys. Lett. B* **411**, 173-179 (1997).
25. Lai, H. L. *et al.* (CTEQ Collaboration). Global QCD analysis and the CTEQ parton distributions. *Phys. Rev. D* **51**, 4763-4782 (1995).
26. Marchesini, G. *et al.* HERWIG: a Monte Carlo event generator for simulating hadron emission reactions with interfering gluons. *Comput. Phys. Commun.* **67**, 465-508 (1992).

Acknowledgements. We are grateful to our colleagues A. Quadt and M. Mulders for reading of the manuscript and comments. We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the Department of Energy and National Science Foundation (USA), Commissariat à L'Energie Atomique and CNRS / Institut National de Physique Nucléaire et de Physique des Particules (France), Ministry for Science and Technology and Ministry for Atomic Energy (Russia), CAPES, CNPq and FAPERJ (Brazil), Departments of Atomic Energy and Science and Education (India), Colciencias (Colombia), CONACyT (Mexico), Ministry of Education and KOSEF (South Korea), CONICET and UBACyT (Argentina), The Foundation for Fundamental Research on Matter (The Netherlands), PPARC (UK), Ministry of Education (Czech Republic), the A. P. Sloan Foundation, and the Research Corporation.

Authors' contributions. We wish to note the great number of contributions made by the late Harry Melanson to the DØ experiment, through his steady and inspirational leadership of the physics, reconstruction and algorithm efforts.

Competing interests statement. The authors declare that they have no competing financial interests.

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顶夸克质量的精确测量

DØ项目合作组*

尽管粒子物理的标准模型是非常成功的，但模型本身解释不了亚原子粒子的质量问题，亚原子粒子的质量被假定来源于粒子与所谓的希格斯玻色子之间的相互作用。本文中，一个名为DØ合作组的国际团队通过伊利诺伊州费米实验室的万亿电子伏特加速器

（Tevatron）得到了顶夸克质量的精确测定，由此有助于限定希格斯玻色子允许质量的范围。结果表明，希格斯玻色子的质量比之前预期的要大，因而需要更大的能量才能产生希格斯玻色子。2012年，位于瑞士日内瓦的欧洲核子研究组织（CERN）的大型强子对撞机终于观测到希格斯玻色子，但其质量比预期的要轻。 [英文](#)

粒子物理标准模型包含了像粒子质量这一类的参数，这类参数起源不清，无法预言，但是其量值可以通过它们之间的相互作用来限定。特别是一直被预言存在但是从未被观测到的希格斯玻色子的质量，可以由顶夸克的质量（ M_t ）和W玻色子的质量（ M_W ）^[1]进行限定。因而， M_t 的精确测量可以更好地指导我们寻找希格斯子，甚至可验证标准模型预言的希格斯子是否与实验数据相符。由于顶夸克成对产生，并在 10^{-24} 秒后就衰变为各种末态，通过衰变的产物来重建其质量是非常困难的。本文提出的技术可以从每一个顶夸克事例中获取更多信息并得到比之前测量值^[2]更高的精度（ $\pm 5.3 \text{ GeV} / c^2$ ）。我们最新的结果结合之前发表的互补衰变模式（全轻衰变模式）的测量值^[3]和目前其余已知的结果^[2]，得到的新的全球 M_t 平均值是 $178.0 \pm 4.3 \text{ GeV} / c^2$ ^[4]。由此，最有可能的希格斯子质量的值从已经被实验^[5,6]排除的 $96 \text{ GeV} / c^2$ 提高到 $117 \text{ GeV} / c^2$ ，这比当前的实验灵敏度要高。在95%置信度水平，希格斯子的质量上限从 $219 \text{ GeV} /$

1995年顶夸克的发现是对标准模型 (SM) 的重要支持之一[7,8]。在众多参数中, 顶夸克的质量尤其反映了标准模型的一些根本特征。这是因为本质上顶夸克是一个无质量的点粒子, 然而通过与预言的希格斯场的相互作用, 顶夸克获得的物理质量大致相当于一个金原子核质量。这个质量如此之大, 使得顶夸克 (和W玻色子一起) 成为一个超常灵敏的研究希格斯场的手段。 M_W 的测量值仅有0.05%的不确定度, 而 M_t 的测量值有3%的不确定度[1]。要进一步缩小希格斯子质量的可能范围, 需要改进这两个量值的精确度。但因为 M_t 的测量值不确定度大, 所以对其精度的改进就格外地重要。正如最近[9,10]已指出的, 标准模型的一个潜在问题在于, 根据当前公认的 M_t 测量值, 最有可能的希格斯子质量[6]落在已被实验排除的区间[5]。准确地认识希格斯子的质量, 对于我们理解标准模型或者标准模型以外的其他可能的物理理论, 都是非常重要的。比如说, 在一大类超对称模型中 (解决标准模型缺陷的首选理论), 希格斯子质量必须小于约135 GeV / c^2 。和标准模型不同的是, 超对称性预言的希格斯子不止一个, 但是其中最轻的那一个的性质基本上与标准模型中的希格斯玻色子相同。因此, 如果类标准模型希格斯玻色子的质量超过135 GeV / c^2 , 这一大类超对称模型就不再被看好。另外, 从大型正负电子对撞机 (LEP) [11]得到的一些超对称粒子当前的限制对 M_t 非常敏感。实际上, 当 M_t 大于179 GeV / c^2 时, 一个联系类标准模型希格斯玻色子及其更重的伴子的主要的超对称参数 ($\tan\beta$) 的限制将完全消失[12]。除了对希格斯玻色子的寻找有影响, 改进 M_t 的测量精度还有其他重要意义, 这个目标也是本文的主要研究问题。 英文

DØ项目在费米实验室的万亿电子伏特加速器 (Tevatron) 上研究了用质子-反质子 ($p\bar{p}$) 对撞产生的顶夸克-反顶夸克 ($t\bar{t}$) 事例[13]。900 GeV的质子 (p) 和900 GeV的反质子 ($\bar{p}$) 对撞释放了1.8 TeV的总能量, 几乎相当于十个金原子核的静止质量。每个顶 (反顶) 夸克几乎立即衰变为一个底 (反底) 夸克 $b(\bar{b})$ 和一个 $W^+(W^-)$ 玻色子。我们重新检查了那些一个W玻色子衰变为一个带电轻子 (电子或者 μ 子) 和一个中微子, 而另一个W玻色子衰变为一个夸克和一个反夸克的事例 (图1)。挑选这些事例所用选择条件及实验数据样本与我们之前发表的获

取顶夸克质量的工作中所用的选择条件和数据样本相同，即对应每pb有125个事例积分亮度的实验数据。（就是说，与DØ实验中测得的结果[14]一致，假定 $p\bar{p}$ 对撞中的 $t\bar{t}$ 在能量为1.8 TeV时产生截面为5.7皮靶，这些数据大概对应于700个 $t\bar{t}$ 对，其中只有部分通过各种可能的衰变模式检测到了。大概有30% $t\bar{t}$ 衰变模式对应于图2归类的轻子+喷注拓扑，其中“喷注”这个词表示夸克分裂产生的成群粒子沿夸克原来的方向平行前进）。主要的背景过程包括多喷注产生（20%，其中的一个喷注被错误地重建为轻子）和与 $t\bar{t}$ 信号有相同拓扑结构的轻子型W衰变的W+喷注产生（80%）。 [英文](#)

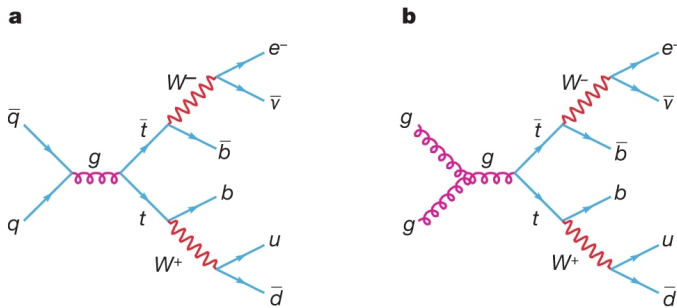


图1 . $p\bar{p}$ （正反质子）对撞中 $t\bar{t}$ （正反顶夸克）产生的费曼图。产生的顶夸克随即衰变为一个电子、中微子和数个夸克。（a）图所示的夸克-反夸克产生过程是主要的，（b）图中的胶子聚变过程贡献大约10%的截面。这个末态 $(e\nu\bar{d}b\bar{b})$ 是分析中用到的通道之一。 [英文](#)

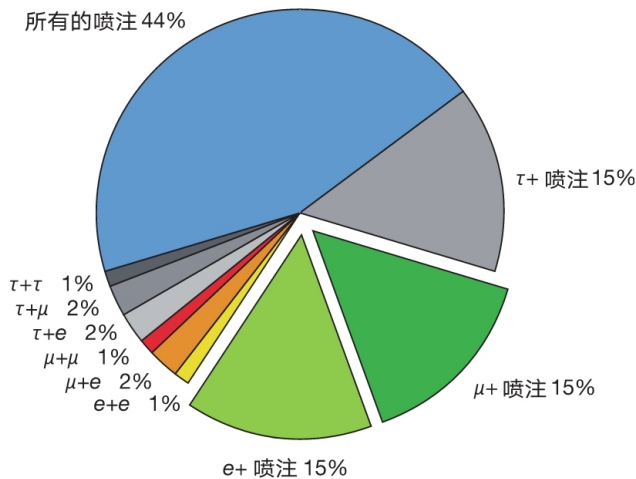


图2 . 各个 $t\bar{t}$ 衰变模式的比例。本分析中用到的“轻子+喷注”衰变道对应于扇面图中分割出的两片，总共占 $t\bar{t}$ 衰变的30%。 [英文](#)

以前在通过轻子+喷注衰变道测量 M_t 值的DØ实验中，根据91个候

选事例得到的量值是 $M_t = 173.3 \pm 5.6$ (统计不确定度) ± 5.5 (系统不确定度) GeV / c^2 。以前的分析以及DØ探测器的相关信息可以在相关文献^[13,15]中找到。 [英文](#)

测量 M_t 的新方法类似于之前文献 (参考文献16以及其中引用的文献, 参考文献17) 提出的关于 $t\bar{t}$ 双轻子衰变道 (其中两个W玻色子的衰变都是轻子型的) 中的测量方法, 该方法曾被应用于之前双轻子事例的质量分析^[3], 与之前建议的在LEP上测量W玻色子质量的方法也是相似的^[18-20]。轻子+喷注衰变道的分析与之前的分析关键的不同之处在于: (1) 测量得比较精确的事例或者更可能对应于 $t\bar{t}$ 信号的事例这点被赋予了更大的权重, (2) 对末态产物 (轻子、喷注和不平衡的横向动量, 最后一项表明了一个未探测到的中微子的存在) 的各种组合的处理以及在事例中用顶夸克衰变产物对它们的确证 (比如解决喷注是对应于 t 夸克衰变中的 b 夸克还是 $\bar{t}$ 夸克衰变中的 $\bar{b}$ 夸克的不确定性问题)。另外, 由于使用领头阶矩阵元计算事例权重, 分析中只保留了恰好有4个喷注的事例, 这样得到的候选样本有71个事例。虽然事例数少了, 但是提取 M_t 的新方法在统计不确定度和系统不确定度上都有实质性的改进。

[英文](#)

我们计算了以 M_t 及事例观测量作为变量的函数, 并将该函数对应为信号的微分概率。这些独立事例概率的最大乘积提供了数据样本中 M_t 的最佳估计值。我们从两个方面考虑了探测器和事例重建算法的不完美引起的偏差影响。几何接收率、触发效率、事例选择等被包含在一个不依赖 M_t 的多元接收函数中。由于事例中所有对象的角度方向和电子动量的测量精度都很高, 它们的测量值被直接用来计算任何对应于 $t\bar{t}$ 事例或者背景事例的产生概率。使用已知的动量分辨率来解释测量喷注能量和 μ 子动量时的不确定度。 [英文](#)

和以前的分析^[13]一样, γ +喷注事例中的动量守恒被用来检查喷注的能量是否与蒙特卡罗 (MC) 模拟结果相符合。这个校准的不确定度 $\delta E = (0.025E + 0.5 \text{ GeV})$ 。因此, 我们的样本中所有喷注能量都以 $\pm \delta E$ 重新标度, 两次重新标度和分析后的 M_t ($\delta M_t = 3.3 \text{ GeV} / c^2$) 结果之差的一半被作为喷注能量测量不确定度引起的系统性不确定度。对系统不确定度有贡献的其他因素包括: 信号和背景的蒙特卡罗建模

($\delta M_t = 1.1 \text{ GeV} / c^2$ 和 $\delta M_t = 1.0 \text{ GeV} / c^2$)，量能器噪声和事例堆积的影响 ($\delta M_t = 1.3 \text{ GeV} / c^2$) 以及其他源于 M_t 提取的修正 ($\delta M_t = 0.6 \text{ GeV} / c^2$)。以上这些因素的贡献要小得多，有另文^[21,22]具体讨论。这里需要指出，新的质量测量方法明显减小了主要由测量喷注能量导致的系统不确定度 (减小了约40%，从 $\pm 5.5 \text{ GeV} / c^2$ 减到 $\pm 3.9 \text{ GeV} / c^2$)。关于新分析方法的细节，请参看本文后面的方法。 [英文](#)

最后的结果是 $M_t = 180.1 \pm 3.6$ (统计误差) ± 3.9 (系统误差) GeV / c^2 。和之前的测量结果比较，新方法在统计不确定度上的改进相当于将数据量增加至原来的2.4倍。将统计和系统不确定度求均方根，我们得到 $M_t = 180.1 \pm 5.3 \text{ GeV} / c^2$ ，这与我们之前在相同衰变道的测量结果相符 (在大约1.4个标准差偏离下)，与之前所有的 M_t 测量的联合精度相当^[1]。 [英文](#)

将新的测量结果与通过第I轮DØ实验 (参考文献3) 中搜集到的双轻子样本得到的结果 ($M_t = 168.4 \pm 12.3$ (统计误差) ± 3.6 (系统误差) GeV / c^2) 相结合，得出顶夸克质量的新的DØ平均：

$$M_t = 179.0 \pm 5.1 \text{ GeV} / c^2 \quad (1)$$

把这一结果和CDF实验的测量结果^[2]进一步结合起来，得到以我们最近的结果为主导的顶夸克质量新的“全球平均” (基于目前所有已知的测量结果) ^[4]：

$$M_t = 178.0 \pm 4.3 \text{ GeV} / c^2 \quad (2)$$

这个新的全球平均将预言的希格斯子质量的最佳拟合值从 $96 \text{ GeV} / c^2$ 提高到 $117 \text{ GeV} / c^2$ (见图3)，现在这个值已经落在了实验排除的区间之外，但可以在Tevatron上目前正运行的实验中以及CERN目前正在建设的大型强子对撞机 (LHC) 上将开展的实验中达到。(在95%置信度水平下，希格斯子质量的上限值从 $219 \text{ GeV} / c^2$ 变为 $251 \text{ GeV} / c^2$)。图3显示如果只采用最新的DØ顶夸克质量来拟合希格斯子质量，获得的最佳

的结果为 $123 \text{ GeV} / c^2$ ，在95%置信度水平下最佳上限值为 $277 \text{ GeV} / c^2$ 。注意图3中水平坐标是对数尺度，因而希格斯玻色子质量的上下限值是不对称的。 英文

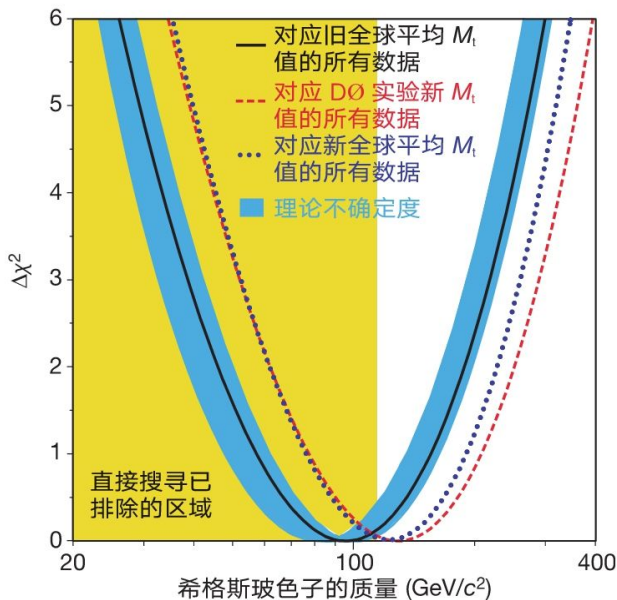


图3．当前实验得出的对希格斯玻色子质量的限定。图中显示电弱数据^[6]全局拟合的 χ^2 值随希格斯子质量的变化。实线对应于之前的全球平均 $M_t = 174.3 \pm 5.1 \text{ GeV} / c^2$ 的结果，蓝色带状区域表示理论不确定度的影响。点线表示新的全球平均 $M_t = 178.0 \pm 4.3 \text{ GeV} / c^2$ 的结果，短横线对应只采用DØ实验新平均值 $179.0 \pm 5.1 \text{ GeV} / c^2$ 的结果。左边黄色阴影区域表示实验排除的希格斯质量范围（ $> 114.4 \text{ GeV} / c^2$ ，95%置信水平下^[5]）。改进后的 M_t 测量值使得最有可能的希格斯子质量移至实验排除的区间之外。 英文

新方法已经被用来处理费米实验室Tevatron上新一轮CDF实验和DØ实验中所收集到的数据，以期得到更精确的 M_t 值，以达到相当于常规方法两倍多数据样本的精度。可以预期经过未来几年在Tevatron上的实验，顶夸克质量的精度最终能够达到 $2 \text{ GeV} / c^2$ 。而更进一步的精度提升最终将有赖于LHC的投入使用。 英文

方法

作为 M_t 函数的概率密度可以表示为可计算的截面与所有来自测量分辨率的效应的卷积

$$P(x, M_t) = \frac{1}{\sigma(M_t)} \int d\sigma(y, M_t) dq_1 dq_2 f(q_1) f(q_2) W(y, x) \tag{3}$$

其中广义传递函数 $W(y, x)$ 表示从一组部分子水平的变量 y 中产生探测器水平变量 x 的归一化概率； $d\sigma(y, M_t)$ 是部分子水平的理论微分截面； $f(q)$ 是部分子的分布函数，表示质子（反质子）内发现处于特定相互作用中、动量为 q 的夸克（反夸克）的概率， $\sigma(M_t)$ 是产生 $t\bar{t}$ 的总截面。式（3）中的积分要对所有可能的部分子态进行求和，从而得到探测器水平的观测结果。 [英文](#)

探测器的接受特性由函数 $A(x)$ 表达。这个函数将观测到的探测器水平变量 x 的概率 $P_m(x, M_t)$ 与其产生概率 $P(x, M_t)$ 联系起来： $P_m(x, M_t) = A(x)P(x, M_t)$ 。能量分辨率等效效应包含在传递函数 $W(y, x)$ 中。式（3）中对11个精确测量的变量（带电轻子动量的3个分量以及8个喷注角度）的积分，加上四个能量-动量守恒关系，使得要完成5次积分才能得到特定 M_t 质量值下任何可代表 $t\bar{t}$ （或者背景）产生事例的概率。

[英文](#)

$t\bar{t}$ 事例判读的概率可以表示为

$$P_{\bar{t}t} = \frac{1}{12\sigma_{\bar{t}t}} \int d^5\Omega \sum_{\text{perm}, x} |M_{\bar{t}t}|^2 \frac{f(q_1)f(q_2)}{|q_1||q_2|} \Phi_6 W_{\text{jets}}(E_{\text{part}}, E_{\text{jet}})$$

其中 Ω 代表一组积分变量（5个），对于 $t\bar{t}$ 产生事例， $M_{\bar{t}t}$ 是其领头阶矩阵元^[23,24]。 $f(q_1)$ 和 $f(q_2)$ 是入射夸克的CTEQ4M部分子分布函数^[25]， Φ_6 是6体末态的相空间因子，求和运算针对喷注的全部12种排列和所有可能的中微子解进行。 $W_{\text{jets}}(E_{\text{part}}, E_{\text{jet}})$ 对应于一个基于蒙特卡罗模拟研究的、将部分子水平的能量 E_{part} 映射到探测器测量到的能量 E_{jet} 的函数。利用一个不依赖 M_t 的 W +喷注产生（主要的背景来源）的矩阵元，一个类似表达式被用来计算背景判读概率 P_{bkg} 。 [英文](#)

对HERWIG（参考文献26，我们用的是5.1版本）蒙特卡罗事例样本的研究表明，新方法能够使得到的 M_t 统计不确定度降低将近一半。这些研究也揭示，获取的 M_t 值存在一个系统漂移，这一漂移依赖于数据中的背景数目。为了尽量减小这一效应，我们根据一个事例代表背景的概率引入了一个遴选程序。应用本方法处理数据之前，根据蒙特卡罗模拟，确定了具体的 P_{bkg} 截断值。对于 $M_t = 175 \text{ GeV} / c^2$ ，71%的信号和30%的背景都得到保留。71个候选事例中，有22个通过了遴选。 [英](#)

最终作为 M_t 函数的似然函数表达式如下：

$$\ln L(M_t) = \sum_{i=1}^n \ln [c_1 P_{\bar{t}}(x_i, M_t) + c_2 P_{\text{bkg}}(x_i)] - N \int A(x) [c_1 P_{\bar{t}}(x, M_t) + c_2 P_{\text{bkg}}(x)] dx$$

积分运算是通过蒙特卡罗方法完成的。 M_t 的最佳值（当 L 等于其最大值 L_{max} ）代表了最终的 N 事例样本中最有可能的顶夸克质量值，参数 c_i 反映信号和背景的数量。蒙特卡罗模拟研究表明获取的质量值有一个向下的 $0.5 \text{ GeV} / c^2$ 的漂移，由此我们对结果进行了修正。在合理范围内 P_{bkg} 截断值的变动对 M_t 没有显著的影响。

英文

图4显示了进行 $0.5 \text{ GeV} / c^2$ 的质量偏差的修正之后，通过所有遴选标准的22个事例的 $L(M_t) / L_{\text{max}}$ 比值随 M_t 的变化。在图中每一个质量数据点，对参数 c_i 取最大似然。图中所示数据的高斯拟合得到 $M_t = 180.1 \text{ GeV} / c^2$ ，统计不确定度 $\delta M_t = 3.6 \text{ GeV} / c^2$ 。如上文所述，系统不确定度主要受喷注能量的测量的影响，大小为 $\delta M_t = 3.9 \text{ GeV} / c^2$ 。系统不确定度与拟合得到的统计不确定度求均方根，得到新的 M_t 测量值的总不确定度为 $\pm 5.3 \text{ GeV} / c^2$ 。

英文

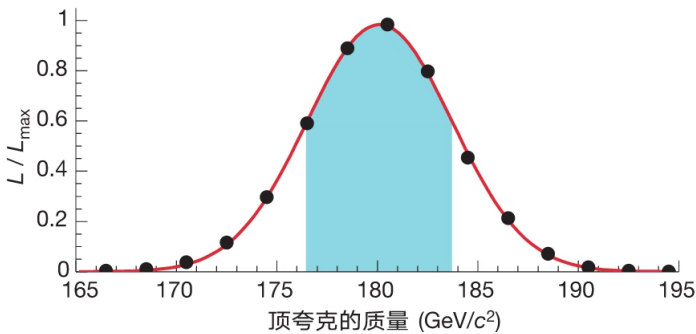


图4．用最大似然法确定顶夸克的质量。数据点表示用以获取 M_t 的拟合的似然值与其最大值的比，该比是 M_t 的函数（已进行 $0.5 \text{ GeV} / c^2$ 的质量偏差的修正，见正文）。实线表示对数据点的高斯拟合结果。最大似然值对应质量为 $180.1 \text{ GeV} / c^2$ ，这也是新的轻子+喷注衰变道中 M_t 的 $D\bar{D}$ 实验测定值。带颜色的区域对应正负一个标准差区间，表示 $\pm 3.6 \text{ GeV} / c^2$ 的拟合统计不确定度。

英文

* 合作组的参与者及所属单位的名单请参见原文。

Experimental Investigation of Geologically Produced Antineutrinos with KamLAND

T. Araki *et al.*

The KamLAND anti-neutrino detector at the Kamioka mine in Japan was the first detector sensitive enough to detect neutrino oscillations—the spontaneous transformation of a neutrino from one type to another—by looking at anti-neutrinos from nuclear reactors. As Takeo Araki and colleagues note here, the detector was also sensitive enough to detect neutrinos produced in the Earth's interior from radioactive decay of uranium or thorium. Previous estimates of the energy released by such decays suggested that it accounted for fully half of the total energy dissipated inside the planet, making radioactivity a significant contributor to the heat of the deep earth. The results here broadly agree with the earlier figures, and put an improved upper limit on its value. [中文](#)

The detection of electron antineutrinos produced by natural radioactivity in the Earth could yield important geophysical information. The Kamioka liquid scintillator antineutrino detector (KamLAND) has the sensitivity to detect electron antineutrinos produced by the decay of ^{238}U and ^{232}Th within the Earth. Earth composition models suggest that the radiogenic power from these

isotope decays is 16 TW, approximately half of the total measured heat dissipation rate from the Earth. Here we present results from a search for geoneutrinos with KamLAND. Assuming a Th / U mass concentration ratio of 3.9, the 90 per cent confidence interval for the total number of geoneutrinos detected is 4.5 to 54.2. This result is consistent with the central value of 19 predicted by geophysical models. Although our present data have limited statistical power, they nevertheless provide by direct means an upper limit (60 TW) for the radiogenic power of U and Th in the Earth, a quantity that is currently poorly constrained. [中文](#)

THE Kamioka liquid scintillator antineutrino detector (KamLAND) has demonstrated neutrino oscillation using electron antineutrinos ($\bar{\nu}_e$ s) with energies of a few MeV from nuclear reactors^{1,2}. Additionally, KamLAND is the first detector sensitive enough to measure $\bar{\nu}_e$ s produced in the Earth from the ²³⁸U and ²³²Th decay chains. Using $\bar{\nu}_e$ s to study processes inside the Earth was first suggested by Eder³ and Marx⁴, and has been reviewed a number of times⁵⁻¹⁰. As $\bar{\nu}_e$ s produced from the ²³⁸U and ²³²Th decay chains have exceedingly small interaction cross-sections, they propagate undisturbed in the Earth's interior, and their measurement near the Earth's surface can be used to gain information on their sources. Although the detection of $\bar{\nu}_e$ s from ⁴⁰K decay would also be of great interest in geophysics, with possible applications in the interpretation of geo-magnetism, their energies are too low to be detected with KamLAND. The antineutrino flux above our detection threshold from other long-lived isotopes is expected to be negligible. [中文](#)

The Radiogenic Earth

The total power dissipated from the Earth (heat flow) has been measured with thermal techniques¹¹ to be 44.2 ± 1.0 TW. Despite this

small quoted error, a more recent evaluation¹² of the same data (assuming much lower hydrothermal heat flow near mid-ocean ridges) has led to a lower figure of 31 ± 1 TW. On the basis of studies of chondritic meteorites¹³ the calculated radiogenic power is thought to be 19 TW, 84% of which is produced by ^{238}U and ^{232}Th decay. Some models of mantle convection suggest that radiogenic power is a larger fraction of the total power^{14,15}. 中文

^{238}U and ^{232}Th decay via a series of well-established α and β -processes¹⁶ terminating in the stable isotopes ^{206}Pb and ^{208}Pb , respectively. Each β -decay produces a daughter nucleus, an electron and a $\bar{\nu}_e$. The $\bar{\nu}_e$ energy distribution is well established¹⁷, and includes a correction for the electromagnetic interaction between the electron and the charge distribution of the daughter nucleus. Figure 1 shows the expected $\bar{\nu}_e$ distribution, $dn(E_\nu) / dE_\nu$, as a function of $\bar{\nu}_e$ energy, E_ν , for the ^{238}U and ^{232}Th decay chains. 中文

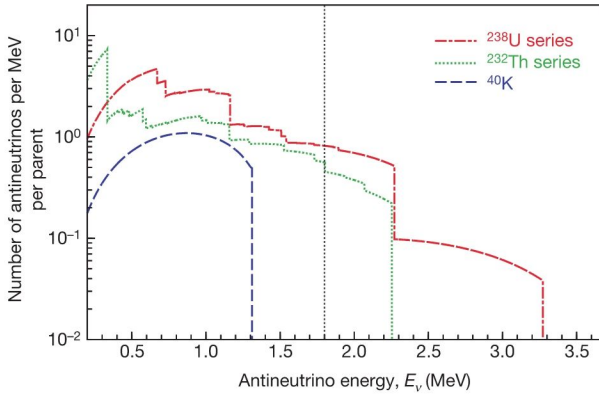


Fig. 1. The expected ^{238}U , ^{232}Th and ^{40}K decay chain electron antineutrino energy distributions. KamLAND can only detect electron antineutrinos to the right of the vertical dotted black line; hence it is insensitive to ^{40}K electron antineutrinos. 中文

Ignoring the negligible neutrino absorption, the expected $\bar{\nu}_e$ flux at a position $\mathbf{r}$ for each isotope is given by:

$$\frac{d\phi(E_\nu, \mathbf{r})}{dE_\nu} = A \frac{dn(E_\nu)}{dE_\nu} \int_{V_\oplus} d^3\mathbf{r}' \frac{a(\mathbf{r}')\rho(\mathbf{r}')P(E_\nu, |\mathbf{r}-\mathbf{r}'|)}{4\pi|\mathbf{r}-\mathbf{r}'|^2} \quad (1)$$

where A is the decay rate per unit mass, the integral is over the volume of the Earth, $a(\mathbf{r}')$ is the isotope mass per unit rock mass, $\rho(\mathbf{r}')$ is the rock density, and $P(E_\nu, |\mathbf{r}-\mathbf{r}'|)$ is the $\bar{\nu}_e$ “survival” probability after travelling a distance $|\mathbf{r}-\mathbf{r}'|$. This probability derives from the now accepted phenomenon of neutrino oscillation, and can be written, for two neutrino flavours as¹⁸

$$P(E_\nu, L) \cong 1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{1.27 \Delta m_{12}^2 [\text{eV}^2] L [\text{m}]}{E_\nu [\text{MeV}]} \right) \quad (2)$$

where $L = |\mathbf{r}-\mathbf{r}'|$. The neutrino oscillation parameters $\Delta m_{12}^2 = 7.9_{-0.5}^{+0.6} \times 10^{-5} \text{ eV}^2$ and $\sin^2 2\theta_{12} = 0.82 \pm 0.07$ are also determined with KamLAND² using reactor $\bar{\nu}_e$ s with energies above those of geoneutrinos, combined with solar neutrino experiments¹⁹. Corrections from three flavour neutrino oscillation (<5%) and “matter effects”²⁰ (~1%) are ignored. For typical geoneutrino energies, the approximation $P(E_\nu, |L|) = 1 - 0.5 \sin^2 2\theta_{12}$ only affects the accuracy of the integral in equation (1) at 1% owing to the distributed $\bar{\nu}_e$ production points. This approximation, used in this paper, neglects energy spectrum distortions. [中文](#)

Geoneutrino Detection

KamLAND is located in the Kamioka mine, 1,000 m below the summit of Mt Ikenoyama, Gifu prefecture, Japan (36° 25'36″ N, 137° 18'43″ E). It detects electron antineutrinos in ~1 kton of liquid scintillator via neutron inverse β -decay,

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (3)$$

which has a well-established cross-section²¹ as a function of E_ν . Scintillation light from the e^+ , “prompt event”, gives an estimate of the incident $\bar{\nu}_e$ energy, $E_\nu \approx E_{e^+} + 0.8 \text{ MeV}$ (neglecting the small neutron recoil), where E_{e^+} is the kinetic energy of the positron plus the electron–positron annihilation energy. With a mean time of ~200 μs ,

the neutron is captured by a proton, producing a deuteron and a 2.2 MeV γ -ray. The detection of scintillation light from this 2.2 MeV γ -ray is referred to as the “delayed event”. The spatial and temporal coincidences between the prompt and delayed events provide a powerful tool for reducing backgrounds, which generally limit the sensitivity in low energy neutrino studies. 中文

A reference model²² is constructed using seismic data to divide the Earth into continental crust, oceanic crust, mantle, core and sediment. Some of these regions are further sub-divided, with each sub-region having different U and Th concentrations. This model assumes that U and Th are absent from the core. The expected geoneutrino flux at KamLAND, including a suppression factor of 0.59 due to neutrino oscillations, is $2.34 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ and $1.98 \times 10^6 \text{ cm}^{-2} \text{ s}^{-1}$ from the ^{238}U and ^{232}Th decay chains, respectively. Including the detection cross-section, the number of geoneutrinos expected at KamLAND from ^{238}U and ^{232}Th decay is $3.85 \times 10^{-31} \bar{\nu}_e$ per target proton per year, 79% of which is due to ^{238}U . Figure 2 shows that a large fraction of the expected geoneutrino flux originates in the area surrounding KamLAND. The effect of local geology was studied extensively in the context of the reference model²² and was found to produce less than a 10% error on the total expected flux. 中文

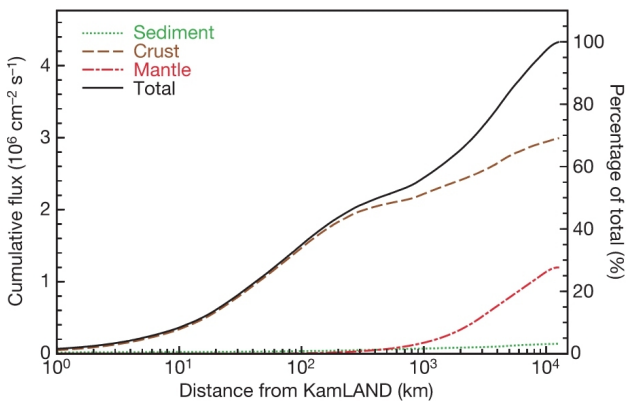


Fig. 2. The expected total ^{238}U and ^{232}Th geoneutrino flux within a given distance from KamLAND²². Approximately 25% and 50% of the total flux originates within 50 km and 500 km of KamLAND, respectively. The line representing the crust includes both the continental

and the almost negligible oceanic contribution. [中文](#)

The data presented here are based on a total detector live-time of 749.1 ± 0.5 d after basic cuts to ensure the reliability of the data. The number of target protons is estimated at $(3.46 \pm 0.17) \times 10^{31}$ on the basis of target proton density and a spherical fiducial scintillator volume with 5 m radius, resulting in a total exposure of $(7.09 \pm 0.35) \times 10^{31}$ target proton years. The overall efficiency for detecting geoneutrino candidates with energies between 1.7 and 3.4 MeV in the fiducial volume is estimated to be 0.687 ± 0.007 . The energy range reaches below the inverse β -decay threshold owing to the detector energy resolution. [中文](#)

Backgrounds for geoneutrino candidates are dominated by $\bar{\nu}_e$ s from nuclear reactors in the vicinity of the detector, and by α -particle induced neutron backgrounds due to radioactive contamination within the detector. Reactor $\bar{\nu}_e$ s reach substantially higher energies, as shown in Fig. 3. Therefore, the oscillation parameters in ref. 2 were determined by analysing $\bar{\nu}_e$ s with energies greater than 3.4 MeV, where there is no signal from the geoneutrinos. Using these parameters, the number of nuclear reactor $\bar{\nu}_e$ background events used by the “rate only” analysis discussed below is determined to be 80.4 ± 7.2 . [中文](#)

The α -particle-induced neutron background is due to the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction where the α -particle is produced in ^{210}Po decay with a kinetic energy of 5.3 MeV. The ^{210}Po is produced by the decay of ^{210}Pb , which has a half-life of 22 yr. The ^{210}Pb resulted from the decay of ^{222}Rn contamination, and is distributed throughout the detector. The neutrons in the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ reaction are produced with kinetic energy up to 7.3 MeV. Owing to scintillation light quenching for high ionization density, only about one-third of this energy is converted into “visible” energy as the neutrons thermalize. The thermal neutrons are captured by protons with a mean capture time of ~ 200 μs ,

producing a delayed signal identical to that from neutron inverse β -decay. The number of ^{13}C nuclei in the fiducial volume is determined from the measured $^{13}\text{C} / ^{12}\text{C}$ ratio in the KamLAND scintillator. On the basis of the $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction cross-section²³, the α -particle energy loss in the scintillator²⁴, and the number of ^{210}Po decays, the total number of neutrons produced is expected to be 93 ± 22 . This error is dominated by estimated 20% and 14% uncertainties in the total $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reaction cross-section and the number of ^{210}Po decays, respectively. The neutron energy distribution is calculated using the measured neutron angular distributions in the centre of mass frame^{25,26}. Including the efficiency for passing the $\bar{\nu}_e$ candidate cuts, the number of (α,n) background events is estimated to be 42 ± 11 .

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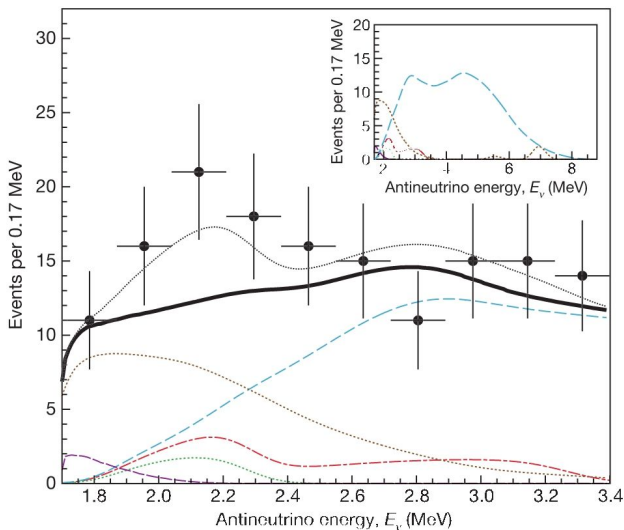


Fig. 3. $\bar{\nu}_e$ energy spectra in KamLAND. Main panel, experimental points together with the total expectation (thin dotted black line). Also shown are the total expected spectrum excluding the geoneutrino signal (thick solid black line), the expected signals from ^{238}U (dot-dashed red line) and ^{232}Th (dotted green line) geoneutrinos, and the backgrounds due to reactor $\bar{\nu}_e$ (dashed light blue line), $^{13}\text{C}(\alpha,n)^{16}\text{O}$ reactions (dotted brown line), and random coincidences (dashed purple line). Inset, expected spectra extended to higher energy. The geoneutrino spectra are calculated from our reference model, which assumes 16 TW radiogenic power from ^{238}U and ^{232}Th . The error bars represent ± 1 standard deviation intervals.

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There is a small contribution to the background from random coincidences, $\bar{\nu}_e$ s from the β^- decay of long lived nuclear reactor fission products, and radioactive isotopes produced by cosmic rays. Using an out-of-time coincidence cut from 10 ms to 20 s, the random coincidence background is estimated to be 2.38 ± 0.01 events. Using the expected $\bar{\nu}_e$ energy spectrum²⁷ for long lived nuclear reactor fission products, the corresponding background is estimated to be 1.9 ± 0.2 events. The most significant background due to radioactive isotopes produced by cosmic rays is from the β^- decay ${}^9\text{Li} \rightarrow 2\alpha + n + e^- + \bar{\nu}_e$, which has a neutron in the final state. On the basis of events correlated with cosmic rays, the estimated number of background events caused by radioactive ${}^9\text{Li}$ is 0.30 ± 0.05 . Other backgrounds considered and found to be negligible include spontaneous fission, neutron emitters and correlated decays in the radioactive background decay chains, fast neutrons from cosmic ray interactions, (γ, n) reactions and solar ν_e induced break-up of ${}^2\text{H}$. The total background is estimated to be 127 ± 13 events (1σ error). [中文](#)

The total number of observed $\bar{\nu}_e$ candidates is 152, with their energy distribution shown in Fig. 3. Including the geoneutrino detection systematic errors, parts of which are correlated with the background estimation errors, a “rate only” analysis gives 25^{+19}_{-18} geoneutrino candidates from the ${}^{238}\text{U}$ and ${}^{232}\text{Th}$ decay chains. Dividing by the detection efficiency, live-time, and number of target protons, the total geoneutrino detected rate obtained is $5.1^{+3.9}_{-3.6} \times 10^{-31} \bar{\nu}_e$ per target proton per year. [中文](#)

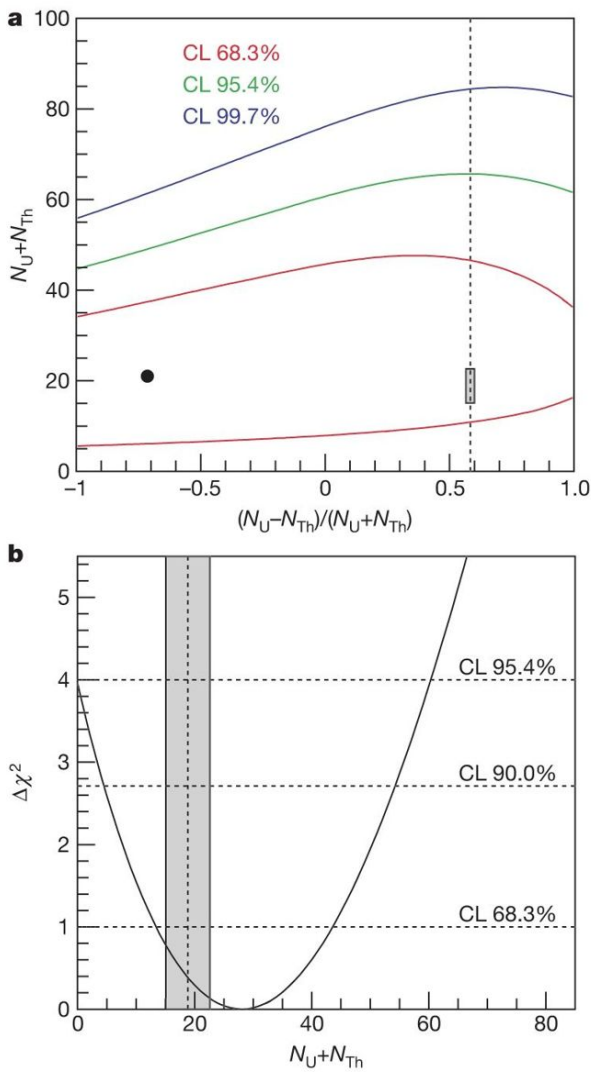


Fig. 4. Confidence intervals for the number of geoneutrinos detected. Panel **a** shows the 68.3% confidence level (CL; red), 95.4% CL (green) and 99.7% CL (blue) contours for detected ^{238}U and ^{232}Th geoneutrinos. The small shaded area represents the prediction from the geophysical model. The vertical dashed line represents the value of $(N_U - N_{Th}) / (N_U + N_{Th})$ assuming the mass ratio, $Th / U = 3.9$, derived from chondritic meteorites, and accounting for the ^{238}U and ^{232}Th decay rates and the $\bar{\nu}_e$ detection efficiencies in KamLAND. The dot represents our best fit point, favouring 3 ^{238}U geoneutrinos and 18 ^{232}Th geoneutrinos. Panel **b** shows $\Delta\chi^2$ as a function of the total number of ^{238}U and ^{232}Th geoneutrino candidates, fixing the normalized difference to the chondritic meteorites constraint. The grey band gives the value of $N_U + N_{Th}$ predicted by the geophysical model. 中文

We also perform an un-binned maximum likelihood analysis of the $\bar{\nu}_e$ energy spectrum between 1.7 and 3.4 MeV, using the known shape of

the signal and background spectra. As the neutrino oscillation parameters do not significantly affect the expected shape of the geoneutrino signal, the un-oscillated shape is assumed. However, the oscillation parameters are included in the reactor background shape. Figure 4a shows the confidence intervals for the number of observed ^{238}U and ^{232}Th geoneutrinos. Based on a study of chondritic meteorites²⁸, the Th / U mass ratio in the Earth is believed to be between 3.7 and 4.1, and is known better than either absolute concentration. Assuming a Th / U mass ratio of 3.9, we estimate the 90% confidence interval for the total number of ^{238}U and ^{232}Th geoneutrino candidates to be 4.5 to 54.2, as shown in Fig. 4b. The central value of 28.0 is consistent with the “rate only” analysis. At this point, the value of the fit parameters are $\Delta m_{12}^2 = 7.8 \times 10^{-5} \text{ eV}^2$, $\sin^2 2\theta_{12} = 0.82$, $p_\alpha = 1.0$, and $q_\alpha = 1.0$, where these last two parameters are defined in the Methods section. The 99% confidence upper limit obtained on the total detected ^{238}U and ^{232}Th geoneutrino rate is $1.45 \times 10^{-30} \bar{\nu}_e$ per target proton per year, corresponding to a flux at KamLAND of $1.62 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$. On the basis of our reference model, this corresponds to an upper limit on the radiogenic power from ^{238}U and ^{232}Th decay of 60 TW. 中文

As a cross-check, an independent analysis²⁹ has been performed using a partial data set, including detection efficiency, of 2.6×10^{31} target proton years. In this analysis, the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ background was verified using the minute differences in the time structures of scintillation light from different particle species. Scintillation light in the prompt part of $\bar{\nu}_e$ events is caused by positrons, whereas scintillation light in the prompt part of $^{13}\text{C}(\alpha, n)^{16}\text{O}$ background events is caused by neutron thermalization. This alternative analysis produced a slightly larger geoneutrino signal, which is consistent with the results presented here. 中文

Discussion and Future Prospects

In conclusion, we have performed the first experimental study of antineutrinos from the Earth's interior using KamLAND. The present measurement is consistent with current geophysical models, and constrains the $\bar{\nu}_e$ emission from U and Th in the planet to be less than $1.45 \times 10^{-30} \bar{\nu}_e$ per target proton per year at 99% confidence limits, corresponding to a flux of $1.62 \times 10^7 \text{ cm}^{-2} \text{ s}^{-1}$. There is currently a programme underway to reduce the ^{210}Pb content of the detector. This should help to reduce the substantial systematic error due to the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ background. Further background reduction will require a new detector location, far away from nuclear reactors. The reported investigation of geoneutrinos should pave the way to future and more accurate measurements, which may provide a new window for the exploration of the Earth. [中文](#)

Methods

As shown in Fig. 5, KamLAND¹ consists of 1 kton of ultrapure liquid scintillator contained in a transparent nylon / EVOH (ethylene vinyl alcohol copolymer) composite film balloon suspended in non-scintillating oil. Charged particles deposit their kinetic energy in the scintillator; some of this energy is converted into scintillation light. The scintillation light is then detected by an array of 1,325 17-inch-diameter photomultiplier tubes (PMTs) and 554 20-inch-diameter PMTs mounted on the inner surface of an 18-m-diameter spherical stainless-steel containment vessel. A 3.2-kton water-Cherenkov detector with 225 20-inch-diameter PMTs surrounds the containment sphere. This outer detector tags cosmic-ray muons and absorbs γ -rays and neutrons from the surrounding rock. [中文](#)

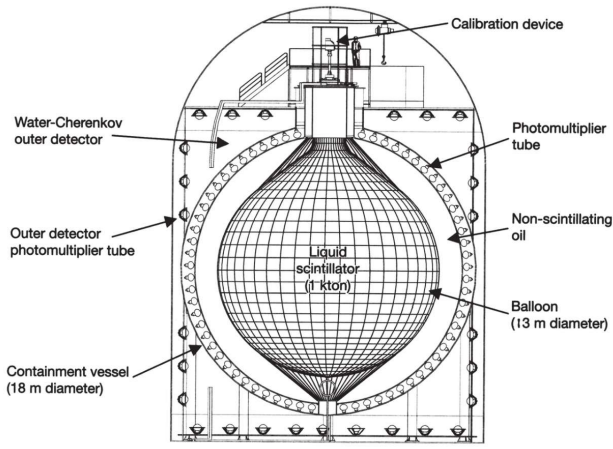


Fig. 5. Schematic diagram of the KamLAND detector. [中文](#)

The arrival times of photons at the PMTs allow us to determine the location of particle interactions inside the detector, and the amount of detected light after correcting for spatial variation of the detector response allows us to determine the particle's energy. The event location and energy determination is calibrated with γ -ray sources deployed vertically down the centre of the detector. To be classified as a $\bar{\nu}_e$ candidate, the time coincidence between the prompt and delayed events (ΔT) is required to satisfy $0.5 \mu\text{s} < \Delta T < 500 \mu\text{s}$. The position of the prompt ($\mathbf{r}_p$) and delayed ($\mathbf{r}_d$) events with respect to the centre of the detector are required to satisfy $|\mathbf{r}_p| < 5 \text{ m}$; $|\mathbf{r}_d| < 5 \text{ m}$ and $|\mathbf{r}_p - \mathbf{r}_d| < 1.0 \text{ m}$: The energy of the electron antineutrino is required to satisfy $1.7 \text{ MeV} < E_\nu < 3.4 \text{ MeV}$ and the energy of the delayed event (E_d) is required to satisfy $1.8 \text{ MeV} < E_d < 2.6 \text{ MeV}$. [中文](#)

Given N_U and N_{Th} geoneutrinos detected from the ^{238}U and ^{232}Th decay chains, the expected energy distribution of the candidates is

$$\begin{aligned} \frac{d\bar{N}(E_\nu)}{dE_\nu} = & N_U \frac{dP_U(E_\nu)}{dE_\nu} + N_{Th} \frac{dP_{Th}(E_\nu)}{dE_\nu} + \frac{dN_i(E_\nu; \Delta m_{12}^2, \sin^2 2\theta_{12})}{dE_\nu} \\ & + P_\alpha \frac{dN_\alpha(E_\nu/q_\alpha)}{dE_\nu} + \sum_k \frac{dN_k(E_\nu)}{dE_\nu} \end{aligned} \quad (4)$$

where $dP_U(E_\nu) / dE_\nu$ and $dP_{Th}(E_\nu) / dE_\nu$ are the normalized expected

geoneutrino spectra from ^{238}U and ^{232}Th decay chains. The third term on the right hand side of equation (4) is the energy spectrum of the expected $\bar{\nu}_e$ reactor background, which is a function of the neutrino oscillation parameters Δm_{12}^2 and $\sin^2 2\theta_{12}$. $dN_\alpha(E_\nu / q_\alpha) / dE_\nu$ is the energy spectrum of the expected $^{13}\text{C}(\alpha, n)^{16}\text{O}$ background with energy and rate scaling factors q_α and p_α , respectively. The sum is over the other known backgrounds where $dN_k(E_\nu) / dE_\nu$ is the expected energy spectrum of the background. All expected spectra include energy smearing due to the detector energy resolution. Integrating equation (4) between 1.7 and 3.4 MeV gives the total number of expected candidates, $\bar{N}$. 中文

The number of geoneutrinos from the ^{238}U and ^{232}Th decay chains is determined from an unbinned maximum likelihood fit. The log likelihood is defined by

$$\log L = -\frac{(N - \bar{N})^2}{2(\bar{N} + \sigma_{\bar{N}}^2)} + \sum_{i=1}^N \log \frac{1}{\bar{N}} \frac{d\bar{N}(E_i)}{dE_\nu} - \frac{(p_\alpha - 1)^2}{2\sigma_p^2} - \frac{(q_\alpha - 1)^2}{2\sigma_q^2} - \frac{\chi^2(\Delta m_{12}^2, \sin^2 2\theta_{12})}{2} \quad (5)$$

where N is the total number of observed candidates and $\sigma_{\bar{N}}$ is the error on $\bar{N}$. E_i is the energy of the i th $\bar{\nu}_e$ candidate. $\sigma_p = 0.24$ and $\sigma_q = 0.1$ are the fractional errors on q_α and p_α , respectively. The term $\chi^2(\Delta m^2, \sin^2 2\theta)$ provides a constraint on the neutrino oscillation parameters from the KamLAND reactor measurements and the solar neutrino results³⁰. $\log L$ is maximized at different values of N_U and N_{Th} by varying Δm_{12}^2 , $\sin^2 2\theta_{12}$, p_α and q_α . The best fit point for N_U and N_{Th} corresponds to the maximum $\log L$. A $\Delta\chi^2$ is defined by

$$\Delta\chi^2 = 2(\log L_{\max} - \log L) \quad (6)$$

where $\log L_{\max}$ is the $\log L$ at the best fit point. The confidence intervals are calculated from this $\Delta\chi^2$. 中文

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Received 25 May; accepted 4 July 2005.

References:

1. Eguchi, K. *et al.* First results from KamLAND: Evidence for reactor antineutrino disappearance. *Phys. Rev. Lett.* **90**, 021802 (2003).
2. Araki, T. *et al.* Measurement of neutrino oscillation with KamLAND: Evidence of spectral distortion. *Phys. Rev. Lett.* **94**, 081801 (2005).
3. Eder, G. Terrestrial neutrinos. *Nucl. Phys.* **78**, 657-662 (1966).
4. Marx, G. Geophysics by neutrinos. *Czech. J. Phys. B* **19**, 1471-1479 (1969).
5. Avilez, C., Marx, G. & Fuentes, B. Earth as a source of antineutrinos. *Phys. Rev. D* **23**, 1116-1117 (1981).
6. Krauss, L. M., Glashow, S. L. & Schramm, D. N. Antineutrino astronomy and geophysics. *Nature* **310**, 191-198 (1984).
7. Kobayashi, M. & Fukao, Y. The Earth as an antineutrino star. *Geophys. Res. Lett.* **18**, 633-636 (1991).
8. Raghavan, R. S. *et al.* Measuring the global radioactivity in the Earth by multidetector antineutrino spectroscopy. *Phys. Rev. Lett.* **80**, 635-638 (1998).
9. Rothschild, C. G., Chen, M. C. & Calaprice, F. P. Antineutrino geophysics with liquid scintillator detectors. *Geophys. Res. Lett.* **25**, 1083-1086 (1998).
10. Mantovani, F., Carmignani, L., Fiorentini, G. & Lissia, M. Antineutrinos from Earth: A reference model and its uncertainties. *Phys. Rev. D* **69**, 013001 (2004).
11. Pollack, H. N., Hurter, S. J. & Johnson, J. R. Heat flow from the Earth's interior: analysis of the global data set. *Rev. Geophys.* **31**, 267-280 (1993).
12. Hofmeister, A. M. & Criss, R. E. Earth's heat flux revised and linked to chemistry. *Tectonophysics* **395**, 159-177 (2005).
13. McDonough, W. F. & Sun, S.-s. The composition of the Earth. *Chem. Geol.* **120**, 223-253 (1995).
14. Jackson, M. J. & Pollack, H. N. On the sensitivity of parameterized convection to the rate of decay of internal heat sources. *J. Geophys. Res.* **89**, 10103-10108 (1984).
15. Richter, F. M. Regionalized models for the thermal evolution of the Earth. *Earth Planet. Sci. Lett.* **68**, 471-484 (1984).
16. Firestone, R. B. *Table of Isotopes* 8th edn (John Wiley, New York, 1996).
17. Behrens, H. & Jänecke, J. *Landolt-Börnstein - Group I, Elementary Particles, Nuclei and Atoms* Vol. 4 (Springer, Berlin, 1969).
18. McKeown, R. D. & Vogel, P. Neutrino masses and oscillations: triumphs and challenges. *Phys. Rep.* **394**, 315-356 (2004).
19. Ahmed, S. N. *et al.* Measurement of the total active ^8B solar neutrino flux at the Sudbury Neutrino Observatory with enhanced neutral current sensitivity. *Phys. Rev. Lett.* **92**, 181301 (2004).
20. Wolfenstein, L. Neutrino oscillations in matter. *Phys. Rev. D* **17**, 2369-2374 (1978).
21. Vogel, P. & Beacom, J. F. Angular distribution of neutron inverse beta decay, $\bar{\nu}_e + p \rightarrow e^+ + n$. *Phys. Rev. D* **60**, 053003 (1999).
22. Enomoto, S. *Neutrino Geophysics and Observation of Geo-neutrinos at KamLAND*. Thesis, Tohoku Univ. (2005); available at http://www.awa.tohoku.ac.jp/KamLAND/publications/Sanshiro_thesis.pdf .
23. JENDL Japanese Evaluated Nuclear Data Library. <http://www.ndc.tokai.jaeri.go.jp/jendl/jendl.html> (2004).

24. Apostolakis, J. Geant—Detector description and simulation tool. <http://wwwasd.web.cern.ch/wwwasd/geant/index.html> (2003).
25. Walton, R. B., Clement, J. D. & Borlei, F. Interaction of neutrons with oxygen and a study of the $C^{13}(\alpha,n)O^{16}$ reaction. *Phys. Rev.* **107**, 1065-1075 (1957).
26. Kerr, G. W., Morris, J. M. & Risser, J. R. Energy levels of ^{17}O from $^{13}C(\alpha, \alpha_0)^{13}C$ and $^{13}C(\alpha,n)^{16}O$. *Nucl. Phys. A* **110**, 637-656 (1968).
27. Kopeikin, V. I. *et al.* Inverse beta decay in a nonequilibrium antineutrino flux from a nuclear reactor. *Phys. Atom. Nuclei* **64**, 849-854 (2001).
28. Rocholl, A. & Jochum, K. P. Th, U and other trace elements in carbonaceous chondrites: Implications for the terrestrial and solar-system Th / U ratios. *Earth Planet. Sci. Lett.* **117**, 265-278 (1993).
29. Tolich, N. *Experimental Study of Terrestrial Electron Anti-neutrinos with KamLAND* Thesis, Stanford Univ. (2005); available at http://www.awa.tohoku.ac.jp/KamLAND/publications/Nikolai_thesis.pdf .
30. KamLAND collaboration. Data release accompanying the 2nd KamLAND reactor result. <http://www.awa.tohoku.ac.jp/KamLAND/datarelease/2ndresult.html> (2005).

Acknowledgements. We thank E. Ohtani and N. Sleep for advice and guidance. The KamLAND experiment is supported by the COE program of the Japanese Ministry of Education, Culture, Sports, Science, and Technology, and by the United States Department of Energy. The reactor data were provided courtesy of the following associations in Japan: Hokkaido, Tohoku, Tokyo, Hokuriku, Chubu, Kansai, Chugoku, Shikoku and Kyushu Electric Power Companies, Japan Atomic Power Co. and Japan Nuclear Cycle Development Institute. Kamioka Mining and Smelting Company provided services for activity at the experimental site.

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KamLAND对地质来源的反中微子的实验研究

荒木岳夫等

KamLAND反中微子探测器位于日本的神冈矿井下。它是第一个足够灵敏到通过监测来自反应堆的反中微子而探测到中微子振荡（即一种类型的中微子自发转变为另一种类型）的探测器。如荒木岳夫及其同事所指出的，该探测器也足够灵敏到可探测地球内部铀和钍放射性衰变产生的中微子。之前的估算表明，这些衰变产生的能量约占地球释放的总能量的一半，这使得放射性成为地球深部热能的一个主要来源。本文的结果与之前的数据大致吻合，并给出了更好的上限值。 [英文](#)

探测地球中天然放射性产生的电子反中微子可以提供重要的地球物理信息。神冈液体闪烁体反中微子探测器（简称KamLAND）可以探测到地球中放射元素 ^{238}U 和 ^{232}Th 衰变产生的电子反中微子（地球中微子）。地球组成模型表明，这些同位素衰变的放射性生热为16 TW，大约占地球总散失热率测量值的一半。本文介绍了KamLAND探测地球中微子的结果。假设Th / U的质量丰度比为3.9，探测到90%置信区间内地球中微子总数为4.5到54.2个。该结果与地球物理模型预测的中心值（19个）一致。尽管现有数据统计量有限，这些数据仍然以直接的方式给出了此前知之甚少的地球中U和Th放射性生热的上限（60 TW）。 [英文](#)

神冈液体闪烁体反中微子探测器（KamLAND）通过对来自核反应堆的几兆电子伏的电子反中微子（ $\bar{\nu}_e$ ）的探测，证明了反应堆中微子振

荡现象^[1,2]。另外，KamLAND也是第一个足够灵敏并探测到地球中²³⁸U和²³²Th衰变链产生的 $\bar{\nu}_e$ 的探测器。埃德^[3]和马克思^[4]第一次提出可利用 $\bar{\nu}_e$ 来测量地球内部性质，之后该观点被引述了数次^[5-10]。²³⁸U和²³²Th衰变链产生的 $\bar{\nu}_e$ 具有极其小的相互作用截面，因此它们不受干扰地在地球内部传播，在地球表面附近对 $\bar{\nu}_e$ 进行测量可获得其产生来源的信息。尽管探测⁴⁰K衰变产生的 $\bar{\nu}_e$ 对地球物理学也具有重要意义，可能用以解释地磁现象，但是它们的能量太低，不能被KamLAND探测到。来自其他长寿命同位素且能量高于我们探测阈值的反中微子被认为可忽略不计。

英文

地球的放射能

地球释放的总能量（热流）已通过热学方法^[11]测得，为 44.2 ± 1.0 TW。尽管以上结果给出的误差很小，最近利用相同数据的推算^[12]（假定洋中脊附近热液的热流低得多）给出一个更低的值 31 ± 1 TW。基于对球粒陨石的研究^[13]，计算出的放射性生热约为19 TW，其中84%来自²³⁸U和²³²Th衰变。一些地幔对流模型给出的放射性生热占总能量的比例更高^[14,15]。

英文

²³⁸U和²³²Th经过一系列已知的 α 衰变和 β^- 衰变后^[16]，最终分别变成稳定同位素²⁰⁶Pb和²⁰⁸Pb。每次 β^- 衰变产生一个子核、一个电子和一个 $\bar{\nu}_e$ 。这个 $\bar{\nu}_e$ 的能谱已经比较精确^[17]，包括对电子和子核电荷分布之间电磁相互作用的修正。图1是来自²³⁸U和²³²Th衰变链的预期 $\bar{\nu}_e$ 分布，即 $dn(E_\nu) / dE_\nu$ ，该结果是 $\bar{\nu}_e$ 能量（ E_ν ）的函数。

英文

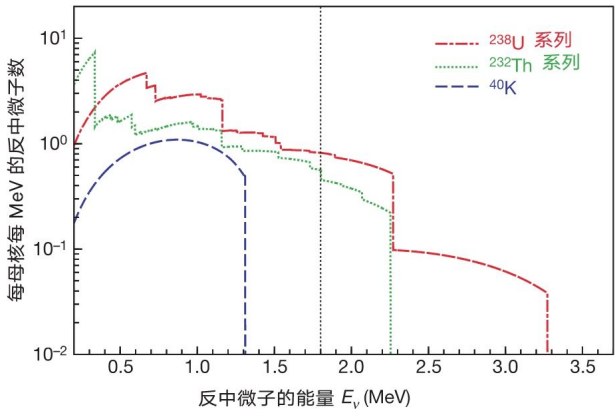


图1．从 ^{238}U 、 ^{232}Th 和 ^{40}K 衰变链产生的电子反中微子的预期能量分布。KamLAND只能探测到黑竖点虚线右侧部分的电子反中微子，因此对 ^{40}K 电子反中微子不敏感。 [英文](#)

忽略微不足道的中微子吸收，每种同位素在位置 $\mathbf{r}$ 处的 $\bar{\nu}_e$ 预期通量如下：

$$\frac{d\phi(E_\nu, \mathbf{r})}{dE_\nu} = A \frac{dn(E_\nu)}{dE_\nu} \int_{V_\oplus} d^3\mathbf{r}' \frac{a(\mathbf{r}')\rho(\mathbf{r}')P(E_\nu, |\mathbf{r}-\mathbf{r}'|)}{4\pi|\mathbf{r}-\mathbf{r}'|^2} \quad (1)$$

其中 A 是单位质量的衰变率，积分针对整个地球的体积进行， $a(\mathbf{r}')$ 是每单位岩体质量的同位素质量， $\rho(\mathbf{r}')$ 是岩石密度， $P(E_\nu, |\mathbf{r}-\mathbf{r}'|)$ 是 $\bar{\nu}_e$ 穿过 $|\mathbf{r}-\mathbf{r}'|$ 距离后的“存活”概率。该概率从已被证实的中微子振荡现象中得来。对两种中微子味道，该概率可写为^[18]

$$P(E_\nu, L) \cong 1 - \sin^2 2\theta_{12} \sin^2 \left(\frac{1.27 \Delta m_{12}^2 [\text{eV}^2] L [\text{m}]}{E_\nu [\text{MeV}]} \right) \quad (2)$$

其中 $L = |\mathbf{r}-\mathbf{r}'|$ 。利用能量高于地球中微子的反应堆 $\bar{\nu}_e$ 的KamLAND实验^[2]，并结合太阳中微子实验^[19]，确定了中微子振荡参数的大小：

$\Delta m_{12}^2 = 7.9_{-0.5}^{+0.6} \times 10^{-5} \text{ eV}^2$ ， $\sin^2 2\theta_{12} = 0.82 \pm 0.07$ 。三味中微子振荡效应（<5%）和“物质效应”^[20]（~1%）的修正可忽略。对典型的地球中微子能量，取 $P(E_\nu, |L|) = 1 - 0.5 \sin^2 2\theta_{12}$ 的近似对公式（1）积分精度的影响只有1%，主要来自分散的 $\bar{\nu}_e$ 产生地点。本文中使用这种近似，忽略了能谱的变形。 [英文](#)

地球中微子探测

KamLAND实验位于日本岐阜县池野山地下1,000米处的神冈矿井中（北纬 $36^\circ 25' 36''$ ，东经 $137^\circ 18' 43''$ ）。它通过中子反 β 衰变过程，在约1千吨的液体闪烁体中探测电子反中微子，

$$\bar{\nu}_e + p \rightarrow e^+ + n \quad (3)$$

该过程的反应截面非常清楚^[21]，是 E_ν 的函数。来自 e^+ 的闪烁光被称为“快信号”，它给出入射 $\bar{\nu}_e$ 的能量的估计值， $E_\nu \approx E_{e^+} + 0.8 \text{ MeV}$ （忽略了小的中子反冲）。此处 E_{e^+} 是正电子动能加上电子-正电子的湮灭能。

经过平均约200 μs 的时间，中子被质子俘获，产生一个氘核和一个2.2 MeV的 γ 光子。探测到的2.2 MeV γ 光子的闪烁光被称为“慢信号”。慢慢信号在时间和位置上的符合提供了一个减少本底的强大工具。在低能中微子研究中，本底通常会制约实验灵敏度。 [英文](#)

利用地震数据构建的一个参考模型^[22]将地球划分为陆壳、洋壳、地幔、地核和沉积层。部分上述区域可进一步细分，每个子区域有不同的U和Th丰度。这个模型假定地核里不含U和Th。预期KamLAND实验站点来自 ^{238}U 和 ^{232}Th 衰变链的地球中微子通量分别为 $2.34 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ 和 $1.98 \times 10^6 \text{ cm}^{-2}\text{s}^{-1}$ ，其中考虑了来自中微子振荡的平均压低因子0.59。考虑探测截面后，KamLAND预期能捕获的来自 ^{238}U 和 ^{232}Th 衰变链的地球中微子事例率为 3.85×10^{-31} 个 $\bar{\nu}_e$ 每靶质子每年，其中79%来自 ^{238}U 。从图2中可以看出，预期的地球中微子通量中，很大一部分在KamLAND附近区域产生。在参考模型中细致地研究了当地的地质效应^[22]，发现导致的误差小于总预期通量的10%。 [英文](#)

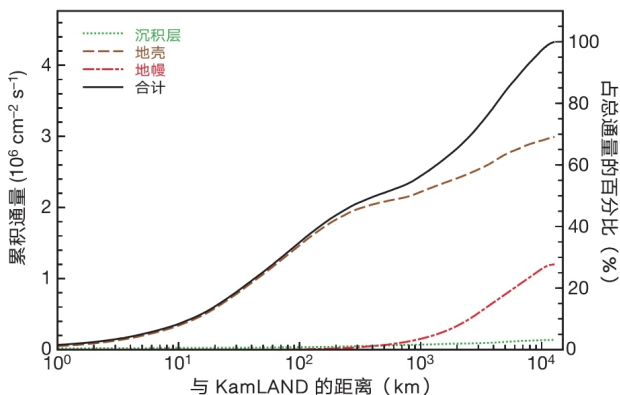


图2：在KamLAND不同距离范围内产生的 ^{238}U 和 ^{232}Th 地球中微子通量^[22]。大约25%和50%的总通量来自KamLAND附近50 km和500 km范围内。图中地壳的贡献包括陆壳和几乎可忽略的洋壳的贡献。 [英文](#)

本文中的数据经过了一些基本挑选，以确保数据的可靠性，总的探测器有效时间为 749.1 ± 0.5 天。基于平均靶质子密度和半径为5 m的闪烁体球形有效体积，总的靶质子数估计为 $(3.46 \pm 0.17) \times 10^{31}$ 个，因此总的曝光量为 $(7.09 \pm 0.35) \times 10^{31}$ 靶质子·年。选取有效体积内能量在1.7 MeV到3.4 MeV之间的地球中微子候选者，总探测效率为 0.687 ± 0.007 。能量范围取到反 β 衰变的阈值以下是因为探测器存在能

量分辨精度。

英文

地球中微子候选者中的本底主要来自探测器附近核反应堆产生的电子反中微子，以及探测器中放射性杂质产生的 α 粒子引发的中子本底。如图3所示，反应堆中微子可达到的能量比地球中微子要高得多。因此参考文献2里的振荡参数通过分析能量大于3.4 MeV的 $\bar{\nu}_e$ 得到，此能量区间内无地球中微子信号。利用这些参数，得到反应堆中微子本底数为 80.4 ± 7.2 ，下面将要介绍的“事例率”分析法中用到此值。 英文

α 粒子引发的中子本底来自 $^{13}\text{C}(\alpha,n)^{16}\text{O}$ 反应，其中 α 粒子来自 ^{210}Po 衰变，动能为5.3 MeV。 ^{210}Po 来自半衰期为22年的 ^{210}Pb 衰变。 ^{210}Pb 来自 ^{222}Rn 衰变，而 ^{222}Rn 污染分布在整個探测器内。 $^{13}\text{C}(\alpha,n)^{16}\text{O}$ 反应产生的中子最大动能为7.3 MeV。由于闪烁光在高电离密度下的淬灭效应，当中子慢化时，只有约三分之一的能量转化为“可见”能量。热中子被质子所俘获，平均俘获时间约为200 μs ，产生一个与中子反 β 衰变相同的慢信号。 ^{13}C 原子核在探测器有效体积内的数量通过测量KamLAND闪烁体的 $^{13}\text{C} / ^{12}\text{C}$ 比值得到。基于 $^{13}\text{C}(\alpha,n)^{16}\text{O}$ 的反应截面^[23]、 α 粒子在闪烁体里的能量损失^[24]以及 ^{210}Po 衰变数，预期产生的总中子数为 93 ± 22 ，误差主要由 $^{13}\text{C}(\alpha,n)^{16}\text{O}$ 反应截面的20%不确定度和 ^{210}Po 衰变数的14%不确定度决定。通过在质心系下测量的中子角分布计算得到中子的能量分布^[25,26]，再考虑 $\bar{\nu}_e$ 事例挑选的效率，估算出 (α,n) 本底大约有 42 ± 11 个。 英文

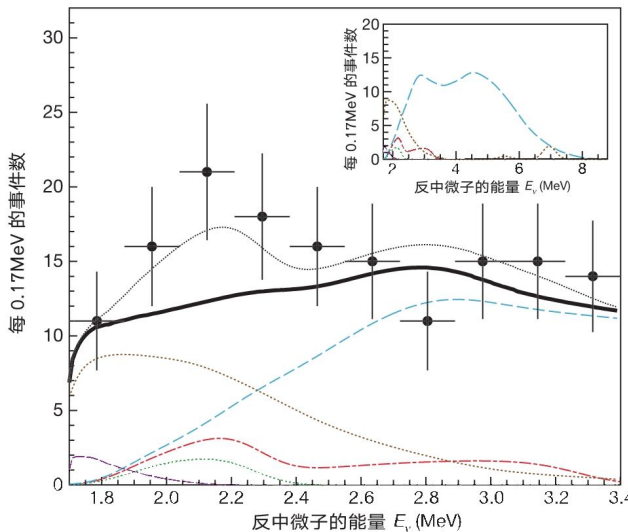


图3 . KamLAND测得的电子反中微子能谱。主图为实验数据点和总的预期能谱（细黑点线）。同时显示了除地球中微子信号外所有预期能谱的总和（粗黑实线）、 ^{238}U 地球中微子预期信号（红点划线）、 ^{232}Th 地球中微子预期信号（绿点线）、反应堆中微子本底（浅蓝虚线）、 $^{13}\text{C}(\alpha, n)^{16}\text{O}$ 反应本底（棕点线）以及随机符合的本底（紫虚线）。小插图显示了延伸到更高能量下的预期能谱。地球中微子能谱从我们的参考模型计算而来，其中假定了 ^{238}U 和 ^{232}Th 共产生16 TW的放射性热能。误差棒代表 ± 1 倍标准偏差。 [英文](#)

其他较小的本底还包括随机符合本底、长寿命的反应堆裂变产物发生 β^- 衰变产生的 $\bar{\nu}_e$ 以及宇宙线产生的放射性同位素。根据信号时间窗以外的10 ms到20 s之间的符合情况来估算，约有 2.38 ± 0.01 个随机符合事例。根据长寿命的反应堆裂变产物的预期 $\bar{\nu}_e$ 能谱[27]，相应的本底估计为 1.9 ± 0.2 个事例。宇宙线产生的最显著的放射性同位素本底来自末态有一个中子的 β^- 衰变 $^9\text{Li} \rightarrow 2\alpha + n + e^- + \bar{\nu}_e$ 。基于与宇宙线关联的事例，由放射性的 ^9Li 产生的预期本底事例为 0.30 ± 0.05 个。其他考虑过但发现可忽略不计的本底还包括自发裂变、放射性本底衰变链中的中子发射和关联衰变、宇宙线产生的快中子、 (γ, n) 反应以及太阳中微子引发的 ^2H 分解。总本底估计为 127 ± 13 个事例（ 1σ 误差）。 [英文](#)

观测到的 $\bar{\nu}_e$ 候选者总数为152个，其能量分布显示在图3中。考虑到地球中微子探测的系统误差（其中一部分与本底估算误差相关联），采用事例率分析法， ^{238}U 和 ^{232}Th 衰变链产生的地球中微子数为 $^{25}_{-18}^{+19}$ 。该事例数除以探测器效率、取数时间以及靶质子数，探测到的地球中微子总事例率为每年每靶质子 $5.1_{-3.6}^{+3.9} \times 10^{-31}$ 个 $\bar{\nu}_e$ 。 [英文](#)

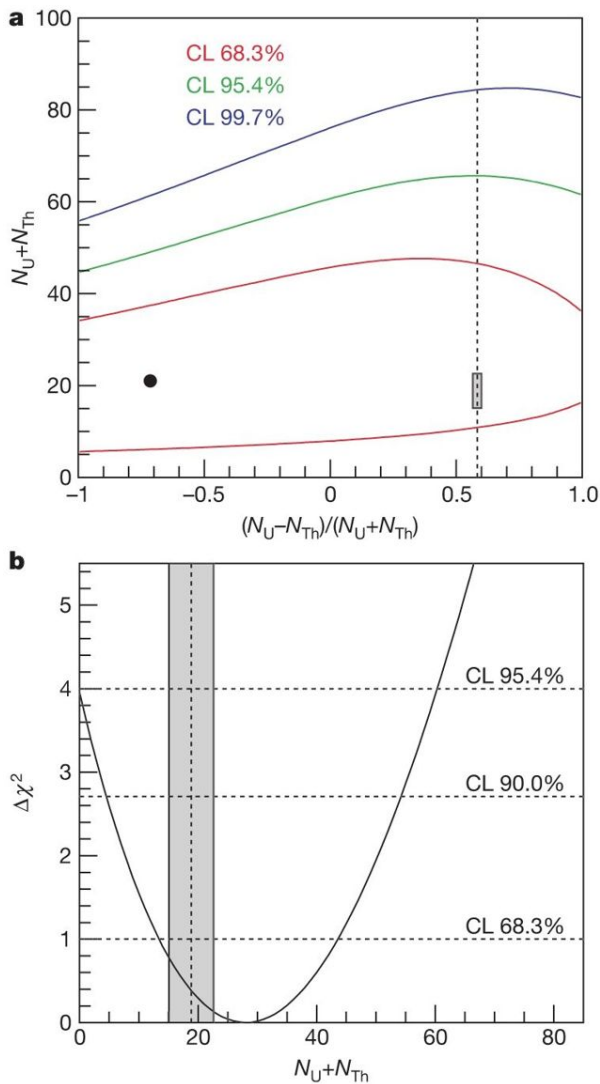


图4．探测到的地球中微子事例数置信区间。图a是探测到的 ^{238}U 和 ^{232}Th 地球中微子数分别在68.3%置信度（红色）、95.4%置信度（绿色）和99.7%置信度（蓝色）下的等值线。小的阴影区是地球物理模型的预期，竖虚线表示基于从球粒陨石推出的Th / U质量比3.9，并考虑了 ^{238}U 和 ^{232}Th 衰变率以及KamLAND对 $\bar{\nu}_e$ 的探测效率等情况下的 $(N_U - N_{\text{Th}})$ 与 $(N_U + N_{\text{Th}})$ 的比值。黑点为最佳拟合点，倾向于 ^{238}U 地球中微子数为3个， ^{232}Th 地球中微子数为18个。图b是 $\Delta\chi^2$ 随 ^{238}U 和 ^{232}Th 地球中微子总数的函数分布，其中归一化后的差别固定到球粒陨石的限制值。灰色区域带是地球物理模型预期的 $N_U + N_{\text{Th}}$ 值。 [英文](#)

我们也利用已知的信号能谱和本底能谱的形状，对1.7~3.4 MeV区间的 $\bar{\nu}_e$ 能谱进行了一项不分能量区间的最大似然分析。中微子振荡参数对预期的地球中微子能谱形状影响很小，因此采用了无振荡的谱形。而

反应堆中微子本底的谱形则包括了振荡参数。图4a显示了观测到的 ^{238}U 和 ^{232}Th 地球中微子数的置信区间。基于对球粒陨石的研究^[28]，地球上Th / U的质量比被认为在3.7~4.1之间，相比于Th和U各自的绝对丰度，人们了解的Th / U质量比是更为准确的。假设Th / U的质量比为3.9，我们估计90%置信区间内 ^{238}U 和 ^{232}Th 地球中微子总数为4.5到54.2，如图4b所示。中心值28.0与前面事例率分析方法的结果一致。此处拟合参数的值分别为 $\Delta m_{12}^2 = 7.8 \times 10^{-5} \text{ eV}^2$ 、 $\sin^2 2\theta_{12} = 0.82$ 、 $p_\alpha = 1.0$ 、 $q_\alpha = 1.0$ ，其中最后两个参数的定义在下面的方法章节中介绍。探测到的 ^{238}U 和 ^{232}Th 地球中微子总事例率的99%置信度上限为 1.45×10^{-30} 个 $\bar{\nu}_e$ 每靶质子每年，对应到达KamLAND的地球中微子通量为 $1.62 \times 10^7 \text{ cm}^{-2} \cdot \text{s}^{-1}$ 。基于我们的参考模型，这相应于 ^{238}U 和 ^{232}Th 衰变的放射性功率上限为60 TW。 [英文](#)

作为验证，使用总量为 2.6×10^{31} 个靶质子·年的部分数据（包含探测器效率）进行了独立分析^[29]。在分析中， $^{13}\text{C}(\alpha, n)^{16}\text{O}$ 本底通过不同粒子种类产生闪烁光的微小时间分布差异得到了验证。 $\bar{\nu}_e$ 事例的快信号是由正电子产生的闪烁光，而 $^{13}\text{C}(\alpha, n)^{16}\text{O}$ 本底事例的快信号是中子慢化产生的闪烁光。此分析得到稍微大一点的地球中微子信号，与本文给出的结果一致。 [英文](#)

讨论和前景

综上所述，我们利用KamLAND探测器，对来自地球内部的反中微子进行了首次实验研究。测量结果与现有的地球物理模型一致：在99%的置信限，限制了地球中U和Th发射的 $\bar{\nu}_e$ 数小于每靶质子每年 1.45×10^{-30} 个，对应于通量 $1.62 \times 10^7 \text{ cm}^{-2} \cdot \text{s}^{-1}$ 。目前正在执行计划以减少探测器中 ^{210}Pb 的含量，这将帮助降低由 $^{13}\text{C}(\alpha, n)^{16}\text{O}$ 本底带来的较大的系统误差。进一步降低本底需要一个新的远离核反应堆的实验点。本文报告的对地球中微子的研究应该为未来更准确的测量铺平了道路，这可能为探索地球提供了一个新的窗口。 [英文](#)

方法

如图5所示，KamLAND^[1]由装在透明的尼龙/EVOH（乙烯-乙烯醇

共聚物)复合膜气球里的1千吨超纯净的液体闪烁体组成,气球悬浮在不产生闪烁光的矿物油中。带电粒子在液体闪烁体里沉积能量,这些能量的一部分转化为闪烁光,被分布在四周的1,325个直径为17英寸的光电倍增管(PMT)和554个直径为20英寸的PMT探测到。PMT安装在直径为18米的球形不锈钢容器的内表面。包围着球形容器的是装有225个直径为20英寸的PMT的3.2千吨水切伦科夫探测器,这个外部探测器用来标记宇宙线μ子并吸收来自周围岩石的γ射线和中子。 英文

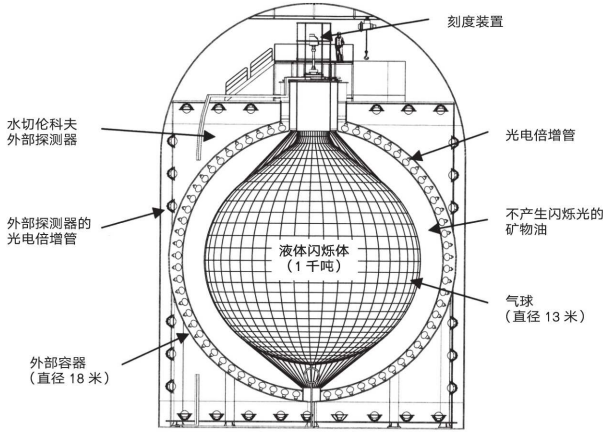


图5 . KamLAND探测器的示意图 英文

根据光子到达PMT的时间分布可确定探测器内粒子发生相互作用的位置。修正探测器响应随位置的变化后,可通过探测到的总光子数确定粒子的能量。事例的位置和能量通过垂伸至探测器中心的γ源进行刻度。对 $\bar{\nu}_e$ 事例的挑选,要求满足以下条件:快慢信号之间的时间符合(ΔT)满足 $0.5 \mu s < \Delta T < 500 \mu s$;相对于探测器中心的快信号($\mathbf{r}_p$)和慢信号($\mathbf{r}_d$)的位置分别满足 $|\mathbf{r}_p| < 5 \text{ m}$, $|\mathbf{r}_d| < 5 \text{ m}$ 以及 $|\mathbf{r}_p - \mathbf{r}_d| < 1.0 \text{ m}$;电子反中微子的能量满足 $1.7 \text{ MeV} < E_\nu < 3.4 \text{ MeV}$;慢信号能量 E_d 满足 $1.8 \text{ MeV} < E_d < 2.6 \text{ MeV}$ 。 英文

假定有 N_U 和 N_{Th} 个探测到的地球中微子分别来自 ^{238}U 和 ^{232}Th 衰变链,预期探测到的全部 $\bar{\nu}_e$ 候选者的能量分布为:

$$\frac{d\bar{N}(E_\nu)}{dE_\nu} = N_U \frac{dP_U(E_\nu)}{dE_\nu} + N_{Th} \frac{dP_{Th}(E_\nu)}{dE_\nu} + \frac{dN(E_\nu; \Delta m_{12}^2, \sin^2 2\theta_{12})}{dE_\nu} + P_\alpha \frac{dN_\alpha(E_\nu/q_\alpha)}{dE_\nu} + \sum_k \frac{dN_k(E_\nu)}{dE_\nu} \quad (4)$$

其中， $dP_U(E_\nu) / dE_\nu$ 和 $dP_{Th}(E_\nu) / dE_\nu$ 分别是 ^{238}U 和 ^{232}Th 衰变链产生的归一化后的预期地球中微子能谱，等式右边第三项是反应堆中微子本底的能谱，它是中微子振荡参数 Δm_{12}^2 和 $\sin^2 2\theta_{12}$ 的函数。 $dN_\alpha(E_\nu / q_\alpha) / dE_\nu$ 是 $^{13}\text{C}(\alpha, n)^{16}\text{O}$ 本底经过能量和事例率的缩放因子 q_α 和 p_α 修正后的预期能谱；最后一项是对已知其他所有本底能谱 $dN_k(E_\nu) / dE_\nu$ 的求和。所有的能谱都包含了由探测器能量分辨引起的能量弥散。对公式（4）在1.7~3.4 MeV能量区间内进行积分给出总的预期 $\bar{\nu}_e$ 事例数 $\bar{N}$ 。 英文

^{238}U 和 ^{232}Th 衰变链产生的地球中微子数目由不分能量区间的最大似然法拟合得到。对数似然函数的定义如下，

$$\log L = -\frac{(N-\bar{N})^2}{2\left(\bar{N} + \sigma_{\bar{N}}^2\right)} + \sum_{i=1}^N \log \frac{1}{\bar{N}} \frac{d\bar{N}(E_i)}{dE_\nu} - \frac{(p_\alpha-1)^2}{2\sigma_p^2} - \frac{(q_\alpha-1)^2}{2\sigma_q^2} - \frac{\chi^2(\Delta m_{12}^2, \sin^2 2\theta_{12})}{2} \quad (5)$$

其中， N 是总的观测事例数， $\sigma_{\bar{N}}$ 是 $\bar{N}$ 的误差， E_i 是第 i 个 $\bar{\nu}_e$ 事例的能量， $\sigma_p=0.24$ 和 $\sigma_q=0.1$ 分别是 p_α 和 q_α 的相对误差。 $\chi^2(\Delta m^2, \sin^2 2\theta)$ 项对KamLAND反应堆中微子测量和太阳中微子测量^[30]得到的振荡参数提供了一个约束。通过改变 Δm_{12}^2 、 $\sin^2 2\theta_{12}$ 、 p_α 和 q_α 这四个参数，将 $\log L$ 在不同 N_U 和 N_{Th} 值处最大化，最大的 $\log L$ 即是 N_U 和 N_{Th} 的最佳拟合点。 $\Delta\chi^2$ 的定义如下

$$\Delta\chi^2 = 2(\log L_{\max} - \log L) \quad (6)$$

其中 $\log L_{\max}$ 是 $\log L$ 在最佳拟合点的值，而置信区间由 $\Delta\chi^2$ 计算得到。

英文

（韩然 翻译；曹俊 审稿）